



REFERENCE ONLY

UNIVERSITY OF LONDON THESIS

Degree *PhD*

Year *2005*

Name of Author *Quoq, B. V.*

COPYRIGHT

This is a thesis accepted for a Higher Degree of the University of London. It is an unpublished typescript and the copyright is held by the author. All persons consulting the thesis must read and abide by the Copyright Declaration below.

COPYRIGHT DECLARATION

I recognise that the copyright of the above-described thesis rests with the author and that no quotation from it or information derived from it may be published without the prior written consent of the author.

LOANS

Theses may not be lent to individuals, but the Senate House Library may lend a copy to approved libraries within the United Kingdom, for consultation solely on the premises of those libraries. Application should be made to: Inter-Library Loans, Senate House Library, Senate House, Malet Street, London WC1E 7HU.

REPRODUCTION

University of London theses may not be reproduced without explicit written permission from the Senate House Library. Enquiries should be addressed to the Theses Section of the Library. Regulations concerning reproduction vary according to the date of acceptance of the thesis and are listed below as guidelines.

- A. Before 1962. Permission granted only upon the prior written consent of the author. (The Senate House Library will provide addresses where possible).
- B. 1962 - 1974. In many cases the author has agreed to permit copying upon completion of a Copyright Declaration.
- C. 1975 - 1988. Most theses may be copied upon completion of a Copyright Declaration.
- D. 1989 onwards. Most theses may be copied.

This thesis comes within category D.

☒

This copy has been deposited in the Library of *UCL*

☐

This copy has been deposited in the Senate House Library, Senate House, Malet Street, London WC1E 7HU.

Applied Economics of Resource Conservation

By Benjamin David Groom

A thesis submitted for
the degree of Doctor of Philosophy
University of London

Department of Economics
University College London
April 2005

UMI Number: U592857

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



UMI U592857

Published by ProQuest LLC 2013. Copyright in the Dissertation held by the Author.
Microform Edition © ProQuest LLC.

All rights reserved. This work is protected against
unauthorized copying under Title 17, United States Code.



ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

To Ana, my love,

and in memory of Sozzle Pyne.

Abstract

This thesis addresses two important topics in environmental and resource economics: social discount rates for the far-distant future and biodiversity conservation and deforestation. In Part 1 social discount rates which decline with time horizon (Declining Discount Rates or DDRs), and their importance for analysing long term projects are discussed. Chapter 1 summarises the recent theoretical and applied literature and highlights some remaining gaps which are the focus of chapters 2 and 3. Chapter 2 solves a puzzle concerning one of the rationales for DDRs set by Gollier 2004a and provides some simple rules for incorporating intergenerational equity into Cost Benefit Analysis (CBA). Chapter 3 discusses the empirical issues surrounding determining a usable schedule of DDRs for CBA. The importance of time series model selection for the interest rate is highlighted.

In Part 2 I focus in international agreements for biodiversity conservation and national policies for reforestation. Chapter 4 models global biodiversity conservation as a North-South bargaining game and shows that current international agreements may provide perverse strategic incentives in their attempt to solve this game and distribute the surplus. One conclusion of this analysis is that the incremental cost compensation for land use changes in the biodiverse south, offered by the Global Environment Facility under the Convention on Biodiversity, may not be sufficient to preclude strategic behaviour and further losses of biodiversity. Following on from this, chapter 5 looks at the household level impact of another important land use compensation policy: the Sloping Lands Conversion Programme (SLCP) of the Peoples Republic of China. We use programme evaluation methods to gauge the impact of the temporary compensation packages offered to participants in the SLCP on the level and source of rural household income, income distribution and poverty alleviation. This allows an analysis of the sustainability of this programme in reaching its objectives.

Contents

Overview	10
Part 1: Time Varying Social Discount Rates	10
Chapter 1: Discounting: the long and the short of it.	10
Chapter 2: Time is the healer: A resolution of the Gollier-Weitzman rift, or: Just keep on discounting at a declining rate but...	12
Chapter 3: Characterising uncertainty in the discount rate: Does model selection affect the certainty equivalent discount rate?	13
Main Results of Part 1	14
Part 2: Biodiversity and Deforestation: The Impacts of International Agreements and National Policies	15
Chapter 4: North-South bargaining in joint production: The biodiversity bar- gaining problem.	15
Chapter 5: The Sloping Lands Conversion Programme of the People's Republic of China: Impacts on income, income distribution and poverty alleviation	17
Main results of Part 2	19
 I Time Varying Social Discount Rates	 21
1 Discounting: The long and the short of it	22
1.1 Introduction	23
1.2 Social Discount Rates: A Brief Review	25
1.2.1 The Ramsey model	25
1.2.2 Interpretation and extensions	27
1.2.3 Selection of the discount rate	30
1.2.4 Common practice and definitions	31
1.3 Declining Discount Rates in a Deterministic World	33
1.3.1 Growth (g) and consumption smoothing (θ)	33
1.3.2 Environmental value and externalities	35
1.3.3 Limitations of the financial markets	38
1.4 Declining Discount Rates in an Uncertain World	40
1.4.1 Uncertainty about the social rate of return (r)	40
1.4.2 The need for an analysis of preferences	43
1.4.3 The effect of uncertain growth (g) on the Social Time Preference Rate (δ)	46
1.5 Intergenerational Equity and Sustainability	50
1.6 Arguments from Behavioural Economics	53
1.6.1 Evidence of hyperbolic discounting	53

1.6.2	Implications of hyperbolic discounting	55
1.7	Practical Implications for CBA	56
1.7.1	A brief summary so far	56
1.7.2	Parameter identification	56
1.7.3	Time inconsistency	59
1.8	Implications of Declining Discount Rates: Some UK case studies	61
1.8.1	Uncertainty of UK interest rates in the future	61
1.8.2	Social cost of carbon	62
1.8.3	Nuclear power	63
1.9	Conclusions	65
1.10	Remaining Issues and Puzzles	68
1.11	References	70
1.12	Appendices	76
1.12.1	Appendix 1. The proof that $\lim_{t \rightarrow \infty} r_a^{CER} = r_{\min}$:	76
1.12.2	Appendix 2. Explicit example of Weitzman's Certainty Equivalent Discount Rate:	77
1.12.3	Appendix 3. The Lucas Tree model:	77
2	Time is the Healer: A resolution of the Gollier-Weitzman rift, or, just keep on discounting at a declining rate but.....	79
2.1	Introduction	80
2.2	The Puzzle Once More	82
2.2.1	Expected net present value (ENPV)	82
2.2.2	Expected Net Future Value (ENFV)	83
2.3	Gollier's Explanation: Risk allocation	85
2.4	The Critique of Gollier (2004a)	86
2.5	An Alternative Explanation: Evaluation date	89
2.6	Project Efficiency and the Evaluation Date	91
2.6.1	Time inconsistency and critical evaluation dates	93
2.6.2	Intergenerational rules for Cost Benefit Analysis	96
2.7	Project Efficiency and Discount Rate Uncertainty	98
2.8	Results with Negative Interest Rates	99
2.9	Conclusion	101
2.10	References	103
2.11	Appendices	104
2.11.1	Appendix 1: Caveats concerning $cov(\tilde{r}, NV(\tau))$ and Proposition 4.	104
3	Characterising uncertainty in the discount rate: Does model selection affect the certainty equivalent discount rate?	109
3.1	Introduction	110
3.2	From Theory to Practice	113
3.2.1	The Certainty Equivalent Discount Factor (CEDR) and Rate (CER)	113
3.2.2	Parameterisation of real interest rates	114
3.3	Empirical Results for the US	118
3.3.1	Data	118
3.3.2	Estimation results	119
3.3.3	Certainty-equivalent discount rates and discount factors: US	122
3.3.4	Model selection	125

3.4	Policy Implications of Model Selection: US	126
3.5	Empirical Results for the UK	128
3.5.1	Data	128
3.5.2	Estimation results	128
3.5.3	Certainty-equivalent discount rates and discount factors: UK	129
3.5.4	Model selection	129
3.6	Policy Implications of Model Selection: UK	132
3.6.1	The value of carbon mitigation	132
3.6.2	The appraisal of investments in nuclear power	133
3.7	Conclusions	134
3.8	References	136
3.9	Appendices: Unit Root Tests and Simulation Method	139
3.9.1	Appendix 1: Unit root tests	139
3.9.2	Appendix 2: Simulations	139

II Biodiversity and Deforestation: The Impacts of International Agreements and National Policies 141

4	North-South bargaining in joint production: The biodiversity bargaining problem	142
4.1	Background	143
4.1.1	North-south cooperation and conflict	143
4.2	Introduction	148
4.3	The Model: Biotechnology and Land Use	151
4.3.1	The North	151
4.3.2	The South	153
4.4	The Biodiversity Bargaining Problem: North-South Conflict and Cooperation	154
4.4.1	The conflict point: Autarky ($s = 0, T = 0$)	154
4.4.2	First best (Social Planner) allocation	155
4.4.3	Bargaining solutions	158
4.5	Investigating the Impact of Current Institutions: Contracts and Intellectual Property Rights	164
4.5.1	The CBD and strategic destruction	164
4.5.2	Bargaining under Intellectual Property Rights (IPRs)	166
4.6	Conclusion	178
4.7	References	180
4.8	Appendices	185
4.8.1	Appendix 1: Proof of Proposition 1	185
4.8.2	Appendix 2: Proof of Example 1: Strategic destruction by the South	186
4.8.3	Appendix 3: Proof of Example 2	187
5	The Sloping Lands Conversion Policy of the People's Republic of China: Impacts on income, income distribution and poverty alleviation	191
5.1	Preamble	192
5.2	Introduction	193
5.3	The Sloping Lands Conversion Policy (SLCP)	197
5.3.1	Motivation and compensation	197

5.3.2	Implementation and institutions	199
5.3.3	Previous analyses of the SLCP: Results and shortcomings	200
5.4	Issues for Estimation of SLCP Impact	201
5.4.1	Heterogeneity, selection and measurement of poverty alleviation	201
5.4.2	The objectives of the current study	204
5.5	Programme Evaluation Methods	206
5.5.1	The program evaluation problem	206
5.5.2	Estimators for non-experimental data	209
5.6	Empirical Strategy	220
5.6.1	Data	221
5.6.2	Participation in the SLCP	225
5.7	SLCP Programme Evaluation: Matching Estimates of Impacts on Household Income	233
5.7.1	Income descriptives	233
5.7.2	Matching estimates of Average Treatment on the Treated (<i>ATT</i>)	237
5.7.3	Summary of average impacts (<i>ATT</i>)	245
5.8	Poverty Alleviation the Distribution of SLCP Impacts	246
5.8.1	Quantile Treatment Effects (<i>QTE</i> (τ))	246
5.8.2	Poverty alleviation	250
5.9	Conclusion	257
5.10	References	261
5.11	Appendices	267
5.11.1	Appendix 1: Procedure for the regression adjusted <i>DID</i> estimators (Heck- man et al 1998, Navarro-Lozano 2004, Abadie 2005) ¹	267
5.11.2	Appendix 2: The data	269
5.11.3	Appendix 3. The propensity score	270
5.11.4	Appendix 4. Household level incomes changes and alternative matching techniques	271
5.11.5	Appendix 5: Regression adjustment results	274
5.11.6	Appendix 6. Poverty alleviation: Alternative estimators	275

¹A routine to implement this estimator written for STATA 8.0 and is available from the author upon request.

List of Figures

1.1	Hyperbolic discount functions.	55
1.2	The profile of carbon damages from the DICE model.	63
1.3	The discounted values of the damage from a ton of carbon	64
2.1	Discount rate schedules for three evaluation dates.	91
2.2	Relative weight on early cash flows increases with evaluation date τ	95
2.3	The effect of discount rate uncertainty on the critical evaluation date.	100
2.4	How $NV(\tau)$ varies with r in a Gollier project	105
2.5	How $NV(\tau)$ varies with r for a Liability project	106
2.6	How $NV(\tau)$ varies with r for a Sequential Project	107
2.7	$NV(\tau)$ when $\tau > 0$	107
4.1	The Bargaining Frontier and Conflict Point	158
4.2	Strategic Destruction as Bargaining Ploy	162
4.3	Strategic Destruction in the PPR model.	173
5.1	Decision tree for participation in the SLCP	228
5.2	Trend in income poverty	254
5.3	SLCP impact on income poverty	255
5.4	SLCP impact on income poverty: Post programme without subsidies	256
5.5	The density of the propensity score	271
5.6	SLCP impact on income poverty: Stratified <i>DID</i> matching	276
5.7	SLCP impact on income poverty: Unmatched <i>DID</i> estimator	276

List of Tables

1.1	Numerical Example of Weitzman's Certainty Equivalent Rate	44
1.2	Effects of DDRs on present values of nuclear power costs and revenues	65
2.1	Two thought experiments on decision criteria and risk allocation.	88
3.1	Estimation Results for the US Models	120
3.2	Certainty Equivalent Discount Factors for the US	124
3.3	Certainty Equivalent Discount Rates for the US	124
3.4	Average MSFEs for the US	125
3.5	Value of Carbon Damages: US models	126
3.6	Estimation results for UK models	130
3.7	Certainty Equivalent Discount Factors for the UK	131
3.8	Certainty Equivalent Discount Rates for the UK	131
3.9	Average MSFEs for the UK	132
3.10	Value of Carbon Damages: UK models	133
3.11	The Costs and Benefits of Nuclear Build in the UK	134
3.12	Unit Root Tests for US Interest Rates	139
3.13	Unit Root Tests for UK interest rates	139
5.1	Guizhou: Descriptive statistics pre-programme	223
5.2	Ningxia: Descriptive statistics pre-SLCP	224
5.3	The model for propensity score: determinants of participation in the SLCP	232
5.4	Per capita incomes in Guizhou province (Yuan 2002 prices)	234
5.5	Per capita incomes in Ningxia province (Yuan 2002 prices)	235
5.6	Per capita incomes for the whole sample	236
5.7	The per capita ATT of the SLCP for the components of household income using matched DID	240
5.8	Regression adjusted estimators for ATT	241
5.9	Quantile treatment on the treated for net incomes	248
5.10	The quantiles of the propensity score	270
5.11	Household level income changes with different DID estimators	272
5.12	Per capita income changes with Stratified and Kernel matching	273
5.13	The ATT for household off-farm labour incomes for participants and non-participants in that market	273
5.14	Regression adjustment estimates for net income per capita	274
5.15	Local linear regression adjustment for net incomes per capita	275

Acknowledgements

In retrospect the pursuit of my doctorate has been more about qualities of persistence than almost anything else. Indeed, I am almost surprised as to the extent of my tenacity. That is, until I realise that I have never been alone in this endeavour and that I managed to sustain my energy only with the continued help of my teachers, colleagues and friends. Only with their help over the past 5 years have I been able to foster my interests, overcome long periods of self doubt, to put my woes into some perspective and, ultimately, maintain an even keel.

In the academic world, the support has been grand. First and foremost my supervisor, Pr. Tim Swanson, has shown extraordinary patience in guiding me given how capricious I can be. The same is true of my other supervisor Pr. David Pearce, to whom I owe much of the inspiration for starting down this road in the first place. It has been tremendously important to me to know that they were on my side and a huge privilege to work with them.

I owe a huge debt to all the people I have been fortunate enough to work with over the past few years. Their influence is present here and it has been a pleasure to work alongside them. In particular, in Part 1, Chapter 1 is the result of long discussions with David Pearce, Cameron Hepburn at Oxford and Phoebe Koundouri at Reading University. Indeed, together with Robin Smale at OXERA we fashioned what must be one of the quickest transitions from theory to policy imaginable: from economic journals to the Treasury Green Book in under 4 months. Chapter 2 represents the fruit of a most enjoyable and illuminating collaboration with Cameron Hepburn. This was enjoyable not only because Cameron is such an incredibly smart and amiable bloke, but also because the intellectual journey occurred alongside an actual one, with discussions taking place in eyeshot of the dreaming spires, the Post Office tower, the Swiss Alps and the Lago Maggiore. It has also benefitted from the comments of Pr. Christian Gollier at Toulouse University, and of course was inspired by his work.

Chapter 3 represents joint work with Dr Phoebe Koundouri, Teo Pantelides and Ekaterini Panopoulou, both from the University of Piraeus in Greece. Again, one couldn't ask to work

with more committed and hard working people. Beyond working on this paper, Phoebe has been a constant source of positivity and support since I arrived at UCL, and a great sounding board for ideas economic or otherwise.

In Part 2, Chapter 4 has come about after long and interesting discussions with, and supervision from, Tim Swanson, Rupert Gatti at Cambridge and Timo Göschl at the University of Heidelberg. It also represents an important contribution to the EU funded BioEcon project and has benefitted from comments from the participants of its many meetings. Erwin Bulte and Daan van Soest require particular mention in this regard.

Finally, Chapter 5 would not have been possible without the vision of my supervisor Tim Swanson, Pr. Shiqiu Zhang at Beijing University, Dr. Andreas Kontoleon of Land Economy in Cambridge and Pauline Grosjean from the University of Toulouse. It is the result of an amazingly successful and exciting collaboration funded by the China Council for International Cooperation on Environment and Development (CCICED) and the Department for International Development (DfID) between the Department of Economics at UCL and the Department of Environmental Sciences at Beijing University. This Chapter has been influenced by numerous discussions with Pauline Grosjean to whom, along with the aforementioned team members and the students of Beida, I owe a particular debt for their hard work in developing the household survey and, in the latter case, collecting the data. I hope the collaboration continues.

I have also had the great pleasure of working with and learning from Pr. Alban Thomas and Dr. Celine Nauges of the University of Toulouse. Hopefully there is more to come in the future.

Beyond this, it would be remiss of me to forget to thank all the waifs and strays with whom I shared the 6th floor at Remax House, particularly Ekin Birol, Katia Karousakis, Eric Reyn, Brett Day, David Maddison, Vicky Chick, Janet Roddy, Pierre, Miguel, Carlos and the ex-CSErGers. Not forgetting the Italians: Mario, Giovanni and Dr Cozzi, I owe you one, at least. At some point or another each of these people has had to face up to my occasionally dour outlook on life, or my ill considered questions, whilst enduring their own doctoral or other travails. You all helped me a lot and I am truly thankful.

In sum, if I have made my way at all in this field it is by hanging onto the coattails of the aforementioned colleagues and friends and although I am not sure that I always held fast, I am incredibly grateful to have been given the opportunity.

Outside of academia there has also been a fair amount of hanging on and out, and there are many people I wish to thank for their support. Firstly, I would never have survived all this without my lover Ana, to whom this tome is dedicated. In addition there is one institution, together with its inhabitants and subsidiary, that has played an extremely important role in keeping everything in perspective over the past 5 years. Respectively, the Castle climbing wall, all who climb in her and the Brownswood Park Tavern. To name names, all the cast of the 'French Connection' and 'Amateurs', specifically Andle'all, Ed Bulman, Scottish John, Matt Wilcox, Chee Wing Pang, Steve Pack, Jo Carter, Drunken disAudrey, Jim, Orsi, Charlie, Flow, Kiwi John, Ozzie John, anyone else called John, Dan, Mils, Chris, Nora, Tumble, Mark Campbell, OJ, Nick, Big James and the rest. Although hanging on was always a problem here, and indeed that was the point, hanging out never was. Thanks.

Also, if I have ever been stoic in the face of my meagre adversity then I have taken my lead from my good friend Zaf who has by far the most complicated life of anyone I know and whom I wish every success. Neither ought I forget Yan, whose various escapes from incarceration also kept me on my toes.

Perversely, perhaps, I would also like to acknowledge those without whom I would probably have finished the doctorate a couple of years ago. Brothers Tom and Charlie Leahy, Tim Jenkins, the Alchemicals and their entourage, and all those present at the Digby nights. Thanks for the memories.

Lastly, to my immediate family, Mum, Dad, Simon and Tim, thanks for your constant support and don't worry, I'm going to get a job now.

Overview

Part 1: Time Varying Social Discount Rates

Part 1 of this thesis concerns social discounting and in particular the use of declining discount rates in the evaluation of public policy with long-term impacts. Chapter 1 introduces the underlying theory for the determination of the social discount rate and introduces the reader to recent contributions on the theory of declining discount rates. The practical implications of this theory are also investigated. The review highlights two anomalies concerning the contributions of Weitzman (1998) and Gollier (2004a), one theoretical and one empirical. These constitute the focus of chapter 2 and chapter 3, which are summarised below.

Chapter 1: Discounting: the long and the short of it.

Chapter 1 provides a detailed overview of the theory that underpins social discounting starting with the familiar Ramsey-Koopmans formulations and axiomatic justifications for constant discounting and moving on to the more recent contributions concerning declining discount rates (DDRs). The use of DDRs is of most consequence in evaluating projects and interventions which have consequences in the extremely long-term, e.g. climate change, and their use has been advocated partly in response to the apparent tyranny of conventional discounting on values accruing to future generations and the issues of inter-generational equity that arise.

Firstly, we explore the social discount rate when costs and benefits expressed in units of consumption, that is where consumption is the numeraire. We then discuss the arguments that have been espoused for the use of DDRs when in a deterministic environment. Contributions here include seminal works by Fisher and Krutilla (1975) and more recent work by Weitzman (1994), both of which relate specifically to the role of environmental linkages in determining the discount rate. Once uncertainty in the discount rate or its determinants is introduced

the arguments for using DDRs become even more compelling. Weitzman (1998, 2001, 2004a, 2004b) and Gollier (2002a 2002b, 2004) provide important contributions in this light helping to pinpoint the conditions under which the social discount rate declines over time. In the former, DDRs are a simple consequence of the convexity of the discount function, the nature of the probability distribution and certainty equivalence analysis in a risk neutral environment. For Gollier, whose work is entrenched in asset pricing and the analysis of the yield curve, the decline in the discount rate schedule is more a question of preferences for risk, precaution and prudence. Lastly, the literature on growth and sustainability has contributed to the debate on DDRs, focussing the role of the utility discount rate. Important contributions include Chichilnisky (1997), Chichilnisky and Heal (1996), Heal (1998) and Li and Löfgren (2000, 2001) each of which show the importance of DDRs for the achievement of particular axioms of intergenerational equity and sustainability.

In the course of this summary a number of anomalies arise, particularly with regard to the work of Weitzman (1998). The strength of his approach, especially for the practitioner of Cost Benefit Analysis (CBA), lies in the apparent ease with which it can be operationalised (see e.g. Newell and Pizer 2003, Weitzman 2001). Indeed, the case for DDRs based on this rationale has recently been accepted by the UK Government and is now incorporated into the Treasury Green book (HM Treasury 2003). However, weakness of this approach include its reduced form nature and assumptions about societal risk preferences: risk neutrality. In particular Gollier (2004a) provides a critique of Weitzman (1998) showing that in the Weitzman framework whether one employs an Expected Net Present Value (ENPV) or Expected Net Future Value (ENFV) evaluation criterion determines whether the burden of risk is placed with current or future generations, and consequently whether the social discount rate is declining or increasing over time. In the absence of societal risk preferences this is a puzzle, since any decision on intertemporal risk allocation seems arbitrary.

Indeed it is these two aspects of the DDR debate that are the focus of Chapter 2 and 3. Chapter 2 resolves the tension between Weitzman (1998) and Gollier (2004a) while Chapter 3 provides guidance in the determination of the empirical schedule of discount rates suggested by Newell and Pizer (2003).

Chapter 2: Time is the healer: A resolution of the Gollier-Weitzman rift, or: Just keep on discounting at a declining rate but...

Chapter 2 addresses the puzzle posed by Gollier (2004a) which has emerged from discussion of the work of Weitzman (1998, 2001).

In a recent paper, Gollier (2004a) provides a simple argument which casts doubt on the validity of Weitzman's argument. Gollier argues that whether or not the certainty equivalent discount rate is declining or, by contrast, increasing depends entirely upon the evaluation criterion that one applies to a particular investment decision. While Weitzman (1998) considers the an Expected Net Present Value (ENPV) criterion when in deriving the declining certainty equivalent rate, Gollier shows that if one maximises an Expected Net Future Value (ENFV) criterion, the resulting certainty equivalent rate is in fact increasing. Gollier goes on to argue that choosing between the two criteria is akin to choosing the location in time of the risk associated with the investment: the ENFV criterion places the risk with the future generations while the ENPV criterion places the risk with the present generation. Naturally, in the risk neutral environment of Weitzman (1998), we cannot rely on economic arguments to guide us in this choice and ultimately, any decision is arbitrary. In response to this puzzle Gollier says about himself and Weitzman:

‘we cannot both be right.....in fact to tell you the truth, I think that we are both wrong’

Chapter 2 shows that the ‘puzzle’ put forward by Gollier has a straightforward resolution and that there is a clear sense in which Weitzman (1998) and Gollier (2004a) *can* both be right. It is demonstrated that the model in Gollier (2004a) does not prove that the discount rate increases with the passage of time. On the contrary, the socially efficient discount rate is declining irrespective of the criteria employed in CBA. However, we demonstrate that Gollier is correct in saying that the discount rate is increasing with one time variable. We prove that as the *evaluation date*, that is the numeraire date employed for assessing the investment, moves further into the future, the discount rate at a particular point in time increases. The latter is the insight discovered by Gollier (2004a) and it is in this sense that both Gollier and Weitzman are both right.

Having proven that the discount rate is a declining function of continuous time it is no surprise to find that decisions can be time inconsistent: this is an important feature of DDRs

applied in CBA. That is, projects which are viable at one evaluation date may not be viable at later evaluation dates purely as a result of the passage of time. In light of this we develop some simple 'intergenerational efficiency' rules to determine how far into the future, that is, for how many generations, a given project would pass a CBA. While not solving the problem of time inconsistency completely, this presents a clear, practical method of evaluation based on internal rates of return by which projects can be ranked taking into account intergenerational equity.

Chapter 3: Characterising uncertainty in the discount rate: Does model selection affect the certainty equivalent discount rate?

From the perspective of the practitioner, although the theoretical discussions about DDRs offer a theoretical path through Baumol's 'dark jungles of the second best' and the apparent intergenerational equity-efficiency trade-off contained therein, they are of little value unless the theory can be operationalised. In the case of Gollier (2002a, 2002b, 2004b) and Weitzman (1998) it is uncertainty that drives DDRs, with regard to future growth and the discount rate respectively, thus the question of implementation is one of characterizing the uncertainty of these primals in some coherent way. However, of these two approaches it is Weitzman (1998) that has proven to be more amenable to implementation mainly because the informational requirements stop at the characterization of uncertainty.

The two applications of Weitzman (1998) that exist have taken different approaches stemming from different interpretations of uncertainty. Weitzman (2001) defines uncertainty by the current lack of consensus on the appropriate discount rate for the very long term. More recently, Newell and Pizer (2003) (N&P) suggest that while we are relatively certain about the level of discount rates currently, there is considerable uncertainty in future. They characterize interest rate uncertainty econometrically which provides a working definition of the CER based upon an econometric model and allows empirical estimation of the CER schedule. These applications bring to light some interesting issues concerning the characterization of interest rate uncertainty. Firstly, in both cases persistence of interest rates is important. In N&P the existence of persistence is an empirical question: does a unit-root exist? This is a question that is not satisfactorily answered by N&P. Furthermore, since there are several additional avenues available for the characterization of interest rate uncertainty than the few that they consider, model selection should be an important consideration for determining the empirical schedule of discount rates.

The empirical issues surrounding N&P are the main concern of this chapter and we build upon the following points. Firstly, given the N&Ps interpretation of uncertainty, model selection is likely to be an important determinant of the CER. Furthermore, tests for stationarity, structural breaks, model misspecification and comparisons among models based upon efficiency criteria should guide model selection for the practitioner. This chapter revisits these issues for US and UK interest rate data and shows that in both cases misspecification testing generates a natural progression away from the simple AR(p) specification used by N&P towards models which explicitly consider changes in the time series process over time.

The practical importance of these points are illustrated using US and UK interest data to estimate the CER schedule and two case studies: climate change and nuclear build. The former allows a direct comparison to the work of N&P, while the latter brings to light the different econometric specifications that are appropriate in the UK context and the limitations of DDRs in resolving the issues of inter-generational equity.

Main Results of Part 1

The main results of part 1 can be summarised as follows:

1. The Gollier-Weitzman Puzzle with regard to the certainty equivalent discount rate is resolved. The schedule of social discount rates in this framework is still declining with the passage of continuous time *à la* Weitzman (1998) however it is increasing with the evaluation date, that is, the date at which the project is evaluated and which provides the temporal numeraire.
2. It is shown that time inconsistency not the choice of evaluation criterion is the main explanation for the anomaly noted by Gollier that the verdict of a project appraisal changes depending upon the evaluation criterion employed.
3. We develop rules for Cost Benefit Analysis that assist the practitioner in coming to terms with the time inconsistency that is inevitable in this environment. The rules are encapsulated by the determination of an intergenerational internal rate of return (IIRR).
4. The issue of model selection in the determination of an empirical schedule of discount rates is shown to be of considerable moment.

5. Model selection using empirical tests shows a natural selection towards models that account for structural breaks in the data, and hence changes in the underlying characterisation of the probability distribution for the discount rate.
6. The practical significance of model selection is highlighted. Using our preferred state space model it is shown that the value of a reduction in atmospheric carbon is increased by over 100% compared to constant discounting, and over 80% when compared to the mis-specified model of Newell and Pizer (2003).

Part 2: Biodiversity and Deforestation: The Impacts of International Agreements and National Policies

Part 2 of the thesis presents two perspectives, one theoretical the other empirical, on another important issue within environmental and resource economics: biodiversity conservation and deforestation. Chapter 4 takes a global perspective on biodiversity conservation and looks at how international institutions capture and share the global benefits of North-South cooperation in biodiversity conservation, and the perverse incentives that these institutions may give rise to. Chapter 5 looks at a national compensation policy for reforestation of cultivated lands in the People's Republic of China. Given the temporary nature of compensation in this policy there is some considerable concern with regard to its long-run sustainability. This chapter analyses the impacts of this policy upon household incomes, income distribution and poverty alleviation, upon each of which the sustainability of the policy depends.

Chapter 4: North-South bargaining in joint production: The biodiversity bargaining problem.

Chapter 4 provides a new perspective on international institutions for the conservation of biological diversity. The need for global cooperation for the conservation of biological diversity has long been understood. In stylized terms, the developed North values highly biodiversity in the developing South. The global nature of the benefits from biodiversity means that the North and South cooperate in arriving at the land-use decisions that determine the amount of biodiversity conserved. This requires an appropriate allocation of their individual physical resources, but an agreement on a reasonable division of the global surplus. The need for coop-

eration is particularly palpable in the biotechnology sector. Research and development (R&D) in biotechnology in the North generates innovations from which both regions stand to gain. However, it is countries in the South that are endowed with the biological diversity required as inputs into biotechnological R&D. North-South exchanges of biodiversity inputs and biotech outputs offer scope for considerable welfare gains if cooperation can be realised.

However, the informational nature of these goods hinders this mutual exchange. Since markets cannot be relied upon to facilitate the exchange of such goods, countries agreed in early 1990s to create international institutions in order to ensure cooperation. The Convention on Biological Diversity (CBD) in 1992 and the Trade-Related Intellectual Property Rights (TRIPS) agreement represent the most pertinent examples of institutions that increase investment into both biotechnological R&D in the North as a result of rents earned on intellectual property; and transfers going into conservation in the South under the Global Environment Facility (GEF), the financial vehicle created by the CBD.

One problem with the institutions thus designed is that by most estimates, the rate of degradation of biodiverse habitats in the South does not seem to have been affected by their introduction. Various explanations are possible: government failure such as perverse subsidies (Margulis 2004), dysfunctional property rights (Southgate 2000), lack of complementary farmers' rights (Soete and Droege 2001), corruption (Smith et al. 2003) etc. However, this chapter argues distinctly that the very institutions designed to stimulate conservation actually create incentives for biodiversity loss.

To understand the underlying biodiversity bargaining problem that gives this chapter its name, we apply the tool of cooperative bargaining theory to derive propositions regarding the bargaining frontier, from which a measure of efficiency of the institutions chosen can be derived, and the set of feasible and individually rational strategies of the bargaining parties. A particular focus of this inquiry is whether – in a manner similar to the idea of ‘rational threats’ posited by Nash (1953) – the degradation of biodiversity is a bargaining option for the South. This approach generates a number of results, chief among which is the prospect that current institutions are not robust to rational threats by the South. In other words, continued degradation of biodiversity may very well be in the interest of the South even in the presence of conservation rewards paid through the GEF. In addition we show that, although the institutional arrangements are globally and individually welfare-improving, they are generally second best. In sum these results suggest a number of policy prescriptions and imply that if

the policy choice is between choosing to protect R&D outputs or R&D inputs, the South may prefer a regime that protects intellectual property rights (such as TRIPS) to the conservation rewards of the GEF.

Chapter 5: The Sloping Lands Conversion Programme of the People's Republic of China: Impacts on income, income distribution and poverty alleviation

Whereas chapter 4 highlighted the potential importance of the nature and level of the compensation scheme in land use policies, in chapter 5 we analyse the actual impact of an important national reforestation compensation scheme: the Sloping Lands Conversion Programme (SLCP) or 'Grain for Green' programme of the Peoples Republic of China. This policy started in 1999 and has two main objectives. Firstly, and primarily, the SLCP intends to generate river basin/watershed related environmental benefits by reforesting currently cultivated highly sloped land in the upper reaches of a number of important river systems. Indeed, the SLCP was hatched in direct response to the loss of topsoil, siltation of streams and the increased flood events witnessed in many river basins in recent years, most notably the Yangtze River and the Chao and Bai rivers in the North East of China, each of which was subject to severe floods in the summer of 1998. The blame for the severity of these floods was placed squarely with deforestation (World Bank 2001). Farmers are compensated for changing their land uses in this way and the relatively generous nature of the compensation package serves the second objective of the policy: rural poverty alleviation. Compensation comes in the form of cash, in-kind grain and occasionally tree-seedlings and technical assistance (Xu et al 2001).

The compensation provided to households under the SLCP is limited in duration to a period of 5 or 8 years, and for this reason, there is great speculation as to whether or not the SLCP will be sustainable in the long-run with regard to its two main objectives: environmental benefits and poverty alleviation (Uchida et al 2004, Xu and Cao 2002, Gong and Xu 2000, CCICED 2000). Of course, these two goals are inexorably linked since participating households will only maintain lands reforested under the SLCP if their welfare in the period after compensation ceases is at least what it was under their former land-use practices. That is, the sustainability of the SLCP requires that the incomes of the poor households that are the stated focus of the programme are permanently raised as a result of the temporary subsidies, and hence some households will need to be lifted permanently out of poverty. But is this likely to happen and if so, how?

Ultimately, the implied hope among policy makers within the Chinese government in this regard is that temporary compensation for setting aside land will enable households to find alternative and more lucrative sources of income which permanently raise household welfare thereby removing incentives to revert back to their former practices when compensation ceases. One obvious way in which increased welfare is envisaged is through the production of forest goods from the forested SLCP land. Other alternatives include increased livestock production or off-farm income. But what has been the impact of the programme on participants compared to non-participants? have the sources of income changed as a result of participation in the SLCP? Has overall income risen? What has been the impact on poverty alleviation? Empirical evidence so far is scant and subject to a number of data and econometric problems.

In order to answer these questions and obtain unbiased and efficient estimates of the impact of the SLCP there are two econometric issues arising from particular features of the intervention and its target group. Firstly, there is the question of selection for participation in the SLCP. While in principle participation in the programme is voluntary, evidence suggests that whether selection is voluntary, compulsory or a mixture of the two, depends upon location. In each case selection is likely to be non-random and based on household and local characteristics that are not always observable to the analyst. Hence, the econometric approach must provide an identification strategy that accounts for this. Secondly, it is well known that there are local and household level determinants of rural poverty (see e.g. Jalan and Ravallion 2002, Park et al 2002) and also that semi-subsistence households differ in the nature and severity of the constraints, frictions and market failures that they face, and which effectively define them (Key et al 2000). Consequently, responses to public interventions such as the SLCP are likely to be extremely heterogeneous both geographically and at the household level. Indeed, this has been shown to be the case in China (Chen and Ravallion 2003). It is clear therefore that any empirical approach which attempts to estimate programme impacts needs to accommodate observable and unobservable heterogeneity in two dimensions: selection into the programme and in the specification of the impact.

In this chapter we go some way towards answering these questions and address these econometric issues. We use programme evaluation techniques whose objective is to ensure that the non-experimental data is used in such a way that the SLCP mimics a randomised control experiment. Using matched difference in differences we obtain estimates of the average impact upon participants compared to non participants (the average treatment on the treated), the impact

across different quantiles of the income distribution (quantile treatment effects) and the impact on poverty alleviation. We define poverty in a conventional manner: the proportion of people living beneath a particular level of income, but this definition gives rise to another question: against which yardstick should this be measured? Given that there is wide disagreement on this issue in China, and given the possibility of heterogeneous impacts at different quantiles of the income distribution, we follow Chen and Ravallion (2003) and assess poverty alleviation against a continuum of poverty lines. Finally, we say something about the sustainability of the SLCP in light of the estimations.

Main results of Part 2

On international agreements for biodiversity conservation

1. Current institutional arrangements in the Convention on Biodiversity (CBD) and its financial mechanism the Global Environment Facility (GEF) represent an ‘extreme point contract’ in that the South is left indifferent between cooperation and non-cooperation.
2. Consequently, the current international institutions which address global biodiversity conservation are not robust to the use of rational threats as a bargaining ploy by the South.
3. Current institutions, including intellectual property rights (IPRs) under the TRIPS agreement, may be globally and individually welfare improving, but they are generally second best.
4. Payment for the stock of biodiversity in addition to payments for incremental costs will be required in order to remove these perverse incentives, contrary to the GEF which only considers the latter.
5. The South may prefer an institution that protects the outputs of biodiversity in R&D, e.g. intellectual property rights, rather than the inputs, that is biodiversity itself, as occurs under the CBD and GEF.

On the Impact and sustainability of the Sloping Lands Conversion Policy:

1. Analysis of the participation decision shows that the SLCP targets low productivity land and yet does not always target the poor.

2. In villages where participation is partly voluntary, poor households self select and are more likely to participate.
3. The temporary compensation increases net household incomes on average for participants in the SLCP.
4. These increases in income come from two sources:
 - i) the compensation itself, which, on average, outweighs the value of lost cultivation, and
 - ii) participants in the SLCP increase activity in the off-farm labour market, with income increasing from this source compared to non-participants.
5. The average increases in income are the result of significant impacts at the lower quantiles of the income distribution, not at the higher quantiles, where the impact of the programme on income is negligible.
6. The impact of the programme on poverty alleviation differs widely depending upon the yardstick against which poverty is measured. In the presence of the compensation, at the commonly used \$2 per capita per day measure, the impact is negligible, however at the \$1 per day and the official poverty line of Y640, there is approximately a 10% reduction in the proportion of households beneath that level.
7. Once subsidies are removed however, although the average level of income for participants is not significantly different from non-participants, and the same can be said for the lower quantiles of income, poverty increases among participants as measured from the lower poverty lines.
8. On balance, the analysis shows that the sustainability of the SLCP is by no means guaranteed once subsidies end, since, given the choice, participants could improve their incomes by reverting back to their former land-uses. This accords with other analysis on these data which shows that up to 60% of households state that they would convert SLCP land to cultivation upon cessation of compensation.

Part I

Time Varying Social Discount Rates

Chapter 1

Discounting: The long and the short of it

Abstract¹

The last few years have witnessed important advances in our understanding of time preference and social discounting. In particular, several rationales for the use of time-varying social discount rates have emerged. These rationales range from the ad hoc to the formal, with some founded solely in economic theory while others reflect principles of intergenerational equity. While these advances are to be applauded, the practitioner is left with a confusing array of rationales and the sense that almost any discount rate can be justified.

Chapter 1 draws together these different strands and provides a critical review of past and present contributions to this literature. In addition to this we highlight some of the problems with employing DDRs in the decision-making process, the most pressing of which may be time inconsistency. We clarify their practical implications, and potential pitfalls, of the more credible rationales and argue that some approaches popular in the environmental economics literature are ill-conceived. Finally, we illustrate the impact of different approaches by examining two investments with long-term consequences, namely global warming prevention and nuclear power.

This introductory chapter serves to isolate some of the questions and puzzles, both theoretical and practical, that have arisen from the literature. Two of these avenues of research constitute the focus of Chapters 2 and 3.

¹This chapter draws from a discussion paper of the same name authored by Ben Groom, Cameron Hepburn, Phoebe Koundouri and David Pearce. The usual disclaimer applies.

1.1 Introduction

Debates about discounting have always occupied an important place in environmental policy and economics. Like all other investment, investment in the environment involves incurring costs today for benefits in the future. Whether a public investment is efficient or not is determined by social cost benefit analysis (CBA). In a competitive economy, the socially efficient level of investment is attained by investing in projects where the net present value (NPV), determined by discounting costs and benefits at the social discount rate (SDR) over the time horizon, is greater than zero. It follows that the level of the SDR is critical in determining whether an individual public investment or policy will pass a CBA test.

Quite separately from arguments over whether the discount rate should be positive or not (e.g. Broome 1992, Olson and Bailey 1981), economists and others have argued at length over which of several potential discount rates should be used as the SDR (e.g. Marglin 1963, Baumol 1968, Lind 1982). Several candidates exist, the most widely recognised of which are the social rate of return on investment (r) and the rate at which society values consumption at different points of time, the Social Rate of Time Preference (δ). The distinction between these discount rates is most important in the second best world in which distortions to the economy, such as corporate and personal taxes or environmental externalities, prevent these rates from being equalised. The choice of SDR is inherently complicated in such situations and is dependent upon wide variety of factors such as the extent to which public investment displaces or generates consumption or private investment throughout the lifetime of the project, the extent to which project risk is captured by the discount rate, and assumptions concerning reinvestment (Lind 1982, Portney and Weyant 1999). However, one thing common to much of the past literature is that, whatever the rate chosen, the relative weights applied to all adjacent time periods would be invariant across the time horizon considered. That is, discounting would be exponential.

A common critique of discounting is that it militates against solutions to long-run environmental problems: for example, climate change, biodiversity loss and nuclear waste, which need to be evaluated over a time horizon of several hundred years. The question arises: What is the appropriate procedure for such long time horizons? There is wide agreement that discounting at a constant positive rate in these circumstances is problematic, irrespective of the particular discount rate employed. With a constant rate, the costs and benefits accruing to generations

in the distant future appear relatively unimportant in present values terms. Hence decisions made today on the basis of CBA appear to tyrannise future generations and in extreme cases leave them exposed to potentially catastrophic consequences. Such risks can either result from current actions, where future costs are carry no weight, e.g. nuclear decommission, or from current inaction, where the future benefits carry no weight, e.g. climate change. The inter-generational issues associated with discounting have puzzled generations of economists. Pigou (1932) referred to the deleterious effects of exponential discounting on future welfare as a ‘defective telescopic faculty’. More recently Weitzman (1998) summarises this puzzle succinctly when he states:

‘to think about the distant future in terms of standard discounting is to have an uneasy intuitive feeling that something is wrong, somewhere’.

Discounting also appears to be contrary to the widely supported goal of ‘sustainability’ which by most definitions implies that policies and investments now must have due regard for the need to secure sustained increases in per capita welfare for future generations (Wald Commission on Environment and Development 1987, Atkinson et al. 1997). Also, by attaching little weight to future welfare conventional discounting appears to ignore any notion of intergenerational equity.

A recently proposed solution to this problem is to use a discount rate which declines with time, according to some predetermined trajectory, this raising the weight attached to the welfare of future generations. It is immediately obvious that using a declining discount rate (DDR) would make an important contribution towards meeting the goal of sustainable development.

So, what formal justifications exist for using a DDR and what is the optimal trajectory of the decline? This paper reviews recent contributions addressing these two issues in different ways. We tie together the different approaches — some deterministic, others based on uncertainty, some based upon intergenerational equity, others on considerations of efficiency — and in so doing we highlight some important theoretical and practical issues that arise with DDRs.

The paper proceeds as follows. Section 1.2 provides a brief review of the theory underpinning social discount rates. Section 1.3 presents the arguments for DDRs in a deterministic world. In Section 1.4 we review the literature on uncertainty and discount rates and show that the argument for DDRs is most compelling here. In Section 1.5, we examine the arguments for DDRs founded on intergenerational equity and in Section 1.6 we summarise some of the hy-

perbolic discounting literature. Practical issues arising from the use of DDRs in policy making are considered in Section 1.7, and two case studies are examined in Section 1.8. Section 1.9 concludes.

1.2 Social Discount Rates: A Brief Review

1.2.1 The Ramsey model

In this Section we take the Ramsey growth model as our starting point and describe the derivation of the socially optimal discount rate. In so doing we provide the general framework in which the ensuing discussion of DDRs takes place and show the relationship between the social rate of time preference δ , the private return to investment, i , the social rate of return to investment, r , and the ‘utility discount rate’ or rate of pure time preference, ρ . Each of these rates is a contender for use as the SDR, where the appropriate discount rate for use in CBA depends upon the numeraire employed. For example, the utility discount rate, ρ , is the appropriate discount rate for costs and benefits that are measured in utility. Alternatively, in the Ramsey model r , i , and δ represent the appropriate SDRs when costs and benefits are measured in consumption equivalents, as is usual practice in CBA. In both cases the SDR represents the rate of change of the value or shadow price of the numeraire (Dasgupta 2001)².

The conventional approach to CBA is based on neoclassical growth theory and underpinned by utilitarian ethics. The utilitarian approach holds the view that individual preferences count, the behaviour that we observe within the economy reflects individuals’ preferences and these preferences ought to be reflected in the societal decision making process³. Where the numeraire is units of consumption, the SDR is endogenously determined within the Ramsey framework by optimal saving, consumption and production decisions over time and in this sense it is preference based. Although there are a number of abstractions in this model, which often exist for the sake of tractability, it represents a useful starting point for the discussion of the discount rate and its economic and ethical content.

In the Ramsey model households wish to maximise the discounted intertemporal sum of utility over an infinite time horizon, discounted at the utility discount rate, ρ . In this way

²The shadow price or accounting price interpretation strictly refers to a decentralised economy, rather than to a social planner.

³See Pearce et al (2003) for a discussion.

we temporarily abstract from the perfectly plausible idea that individuals have different rates of pure time preference, ρ_i . Households are modelled as an infinitely lived representative agent whose intertemporal welfare is assumed to be time-separable. In continuous time the maximand for the representative agent is therefore:

$$U(c(t)) = \int_0^{\infty} u[c(t)] \exp(-\rho t) dt \quad (1.1)$$

where the felicity function, $u(\cdot)$, is time invariant and has the following properties: $u'(\cdot) > 0$, $u''(\cdot) \leq 0$ ⁴. Households can supply labour and earn a wage income $w(t)$ and are assumed to hold assets: loans or ownership claims to capital, $a(t)$, which earn a rate of interest $r(t)$, which is taken as given. The associated flow budget constraint can be written as:

$$\dot{a} = w(t) + r(t)a(t) - c(t) \quad (1.2)$$

Firms are also modelled in the Ramsey model. Profit maximising firms rent capital, k , from households at a rental price, R , to produce output, y , using a concave production technology, $f(k)$. They do so up to the point at which the marginal return to capital equals the rental price: $f'(k) = R$. Since capital, k , and loans, are assumed to be perfect substitutes as a store of value, it must be the case that their prices are equal: $R = r$ (Barro and Sala-i-Martin 1995)⁵. Furthermore, in the absence of externalities and other distortions, it must be the case that the social marginal return to capital coincides with the private rate of return, i . It is well known that the solution to this yields the familiar Ramsey rule⁶:

$$i = r = \rho + \theta g = \delta \quad (1.3)$$

where $g = \dot{c}/c$, and θ represents the preferences for smoothing consumption over time and is known as the elasticity of inter-temporal substitution. θ is a measure of the curvature of the utility function and is mathematically equivalent to the coefficient of relative risk aversion: $\theta = -\frac{u''}{u'}c$.

⁴Where $u'(\cdot)$ represents the first derivative with respect to c , $u''(\cdot)$ the second, etc. This notation holds throughout the paper and for other functions where no confusion arises.

In the Ramsey model, the felicity function is also assumed to satisfy the Inada conditions: $u'(c) \rightarrow 0$ as $c \rightarrow \infty$ and $u'(c) \rightarrow \infty$ as $c \rightarrow 0$.

⁵For simplicity we abstract from depreciation, population growth and technological changes here.

⁶See for example Barro and Sala-i-Martin (1995, p63) for a clear derivation.

The left hand side of (1.3) reflects the return to saving: the rate of interest r , which must equal the social and private marginal productivity of capital. The right hand side can be thought of in a number of ways. We have defined the term δ as the social rate of time preference, which reflects the change in relative value that society places on units of consumption at adjacent periods of time. The right hand side of (1.3) can also be thought of as the rate of return to consumption and as a consequence it is frequently referred to as the Consumption Rate of Interest (CRI). In general, δ and CRI are considered to be conceptually different, the former representing the intertemporal weights placed on consumption by society, and the latter representing the same but for individuals. It is frequently the case that the latter is used to measure the former using observed rates of return on savings (Lind 1982).

In sum, Equation (1.3) shows that on the optimal path in the competitive economy individuals (the social planner) will choose their consumption and savings such that their consumption rate of interest (social rate of time preference) is equal to the rate of interest on savings. Likewise, firms will employ capital such that the rate of return is equal to the rate of interest in the economy. In the competitive economy without distortions, social and private rates of return coincide.

1.2.2 Interpretation and extensions

Ramsey interpreted Equation (1.1) as the maximand of an infinitely lived representative agent acting as a trustee for current and future generations in choosing consumption and saving. Central to this interpretation is a bequest motive: the infinitely lived agent reflects an immortal extended family containing many finitely lived altruistic families. These families are connected by a series of intergenerational transfers to their children who in turn give to their children etc. Although there has been criticism of this approach, there is at least some agreement that this abstraction represents a convenient framework for long-term analysis (Tóth 2000, Stephane et al. 1997, Manne 1995)⁷.

One deficiency from the perspective of environmental economics is the absence of explicit consideration of stocks and flows of environmental assets. This deficiency has been addressed in numerous papers in the realm of optimal growth in which stocks of environmental resources

⁷Manne (1995) and Stephan et al. (1997) compare this approach to an Overlapping Generations model (OLG) in the context of climate change policy and find that the OLG model offers little in the way of additional policy insights.

$(s(t))$ are explicitly introduced as a determinant of utility in order to represent amenity values and other preferences for the environment (see e.g. Brock 1977, Heal 1998, Chichilnisky 1997, Li and Lofgren 2000). In such cases instantaneous utility is represented by $u(c(t), s(t))$, and the behaviour of environmental stocks captured by associated equations of motion reflecting the extent to which the resource is renewable and the impact of consumption or production on the environment. Such analyses are frequently directed to the question of optimal and sustainable growth and are also explicitly concerned with notions of intergenerational equity. In effect, such approaches extend the realm of preferences that count in CBA to more explicitly include those of future generations.

Ramsey (1928) described the discounting of utility, that is, placing different weights upon the utility of different generations, as 'ethically indefensible'. Harrod (1948) famously stated that discounting utility represented 'rapacity and the conquest of reason by passion'. Ramsey reflected this belief in his analysis of optimal growth by assuming that $\rho = 0$, and since that time these opinions have been the subject of much contemplation by economists and philosophers alike⁸. However, given (1.3) it should be clear that this by no means implies that costs and benefits measured in units of consumption should not be discounted. With positive growth and concave utility the SDR will be positive, hence discounting consumption streams in CBA can be synonymous with the equal treatment of generations' welfare (Lind 1995).

It is common in theoretical work to employ a positive, time invariant utility discount rate reflecting both alternative beliefs about time preference and the need for tractability. This practice is not without some theoretical basis. Olson and Bailey (1981) look at the implications of assuming $\rho = 0$ for optimal consumption paths. One finding is that the high levels of saving implied by this assumption do not tally well with the empirical evidence. This, they argue, provides a strong rationale for assuming a positive rate of time preference. In a more general preference framework, Koopmans (1960) took an axiomatic approach to this inherently ethical question. He showed that the existence of impatience, that is, the use of a positive utility discount rate, which is constant over time ($\rho > 0$, $\rho_t = \rho$) is implied by the presence of a number of very particular axioms concerning the intertemporal welfare function $U(c)$, among

⁸There are a number of arguments either way concerning utility discounting. Economists' arguments for $\rho > 0$ are frequently concerned with the high level of savings and the immiserisation of current generations that may result in the traditional infinite horizon model. Others suggest that since impatience is observed among individuals it should be reflected in the decision making process. Philosophers and economists alike are not agreed that these arguments are entirely satisfactory.

other things. For example, $U(c)$ must be continuous in its arguments, stationary over time and satisfy a condition known as ‘period independence’. That is, preferences for benefits and costs at a particular period of time are independent of those in the past or future.

Indeed, Koopmans went on to show that the same axioms imply that $U(c)$ takes the time-separable form shown in (1.1). Of course, like any separability assumption, time-separable preferences are not entirely defensible and are considered by many to be problematic. Barro and King (1984) for example, show how time-separability places restrictions upon the relative responses of consumption and leisure to changes in relative prices and permanent income. Intuitively, it seems unlikely that current and future *tastes* will be independent of decisions made in the past.

Discounting utility at a constant rate, ρ , insures the decisions made by the representative agent/social planner are time consistent, that is, the planner will not change his plan purely as a result of the passage of time (Heal 1998, Gollier 2002a). Indeed, time consistency and Koopman’s period independence assumption are closely related. One feature of discount rates that vary over time, on the other hand, is that they tend to invoke time inconsistent behaviour and all its associated travails (Strotz 1956, Barro 1999, Hepburn 2003). In this regard, in addition to the theoretical and ethical arguments concerning the utility discount rate, a great deal of attention has been paid to the discount rates that individuals actually employ. The so-called hyperbolic discounting literature provides considerable evidence that individuals use time varying discount rates in their everyday decision making (e.g. Frederick et al. 2002, Loewenstein and Prelec 1992, Henderson and Bateman 1995). It is frequently posited that such time preferences can explain behaviour as diverse as ‘savouring’ or ‘dread’ effects and seemingly irrational behaviour such as addiction and other ‘slippery slope’ phenomena. Weitzman (1998) notes that, although this behaviour typically refers to short-run behaviour there is an evolutionary argument for using time varying discount rate for the longer term: since we only observe those who survive, hyperbolic discounting must be an effective survival strategy. Similar ideas are developed by Dasgupta and Maskin (2002). Such observations generate something of a puzzle when one considers the ethical underpinning of CBA described above, that is, that preferences count. The evidence raises the question: Is a model of time preferences that describes irrational and often inefficient behaviour a suitable model for social CBA? This is an issue that is discussed further in Section 1.6.

The discussion in the previous Sections has shown that to a great extent the social discount

rate can be considered to be a derived concept. In the Ramsey world the SDR emerges from the optimising economy, while, Koopmans focussed the discussion about the utility discount rate on the underlying axioms of intergenerational justice that one is prepared to adhere to. In this sense the SDR is not ‘ethical raw material’ (Dasgupta 2001).

1.2.3 Selection of the discount rate

The Ramsey rule in Equation (1.3) shows why it is valid to consider the social rate of time preference, δ , and the rate of return on capital, from hereon r , as candidates for the socially efficient discount rate for projects or policies whose costs and benefits are measured in consumption equivalents. If projects are to be financed by current consumption or investment then the rate of return on these projects ought to be compared to that which prevails in the economy. Investment will be efficient if projects are selected in this way. In the perfectly competitive paradigm all rates are equal and hence it does not matter which rate; i , r , or δ , is used for CBA.

Furthermore, true to the ethical underpinning of CBA described above, the Ramsey rule reflects the particular facets of individual preferences that provide the rationale for discounting the future in a deterministic world: 1) *impatience*, reflected by the utility discount rate or pure rate of time preference, ρ , and 2) *the wealth effect* represented by the term θg , where θ is greater than zero if households are averse to consumption fluctuations⁹. The wealth effect describes how individuals will place less value upon additional units of consumption in the future if their belief is that incomes at that time will be higher as a result of economic growth. This effect will be amplified if there is a strong desire to smooth consumption over time. As we shall see in Section 1.4, when uncertainty with regard to growth is introduced, preferences for risk also play a role in determining the socially efficient discount rate, as reflected by the coefficient of relative risk aversion: θ .

In reality, it will not be true that $i = r = \delta$ and the debate about discounting has concerned when and whether it is appropriate to use i , r or δ , or some combination thereof (Lind 1982, Baumol 1968). For example, assuming for the moment that $i = r$, distortionary income and corporation or profit taxes will in general cause the rate of return on capital to differ from the social rate of time preference. In general it will be the case that $r > \delta$ ¹⁰. Imperfect

⁹This is so if the felicity function is concave: $u'(\cdot) > 0$ and $u''(\cdot) < 0 \implies \theta > 0$.

¹⁰to see this consider the following example. If corporation taxes are 50% and income taxes are 25% then if

competition and externalities in production will cause private and social rates of return to capital to diverge: $i \neq r$. Furthermore, the appropriate discount rate for a particular project will depend upon the extent to which a project is funded by consumption or by displaced private investment. It has been argued that, other things equal, a project funded entirely by consumption should be discounted by δ while a project funded entirely by the latter should be discounted by the private rate of return on capital, i (Lind 1982). Subsequently, others have suggested that projects funded by a mixture of the two should be discounted at a rate which reflects an average of the two rates, weighted by the proportions in which consumption and private investment finance the project (Haveman 1969). Another suggestion is to convert all costs and benefits into consumption equivalents using the *shadow price of capital* approach and then to use the δ as the SDR (see e.g. Bradford 1975)¹¹. In addition to these factors, the rate of reinvestment of returns and the riskiness of private versus public investments are also considered to be determinants of the socially efficient discount rate (Baumol 1968). With regard to risk it is commonly thought that the risk free rate of return is appropriate for the appraisal of public projects due to risk pooling available to governments. (Samuelson 1964, Arrow 1966, Lind 1982). Nevertheless, each of these factors requires consideration when determining the correct level of the discount rate in what Baumol called the ‘dark jungles of the second best’ (Baumol 1968).

1.2.4 Common practice and definitions

There are many factors that need to be considered when determining the socially efficient discount rate for use in CBA. This leads to the difficult prospect of different discount rates for different projects (Lind 1982). It is common practice for governments to abstract from detailed adjustments, such as those described above, and employ more practical rules of thumb.

$\delta = 6\%$ then when firms invest they must pay dividends to shareholders such that they obtain a 6% return. This means that the shareholders must earn a pretax profit of 8% (plus 25%) while investors/firms must earn 16% (plus 50%). I.e. $i = 16\%$, $\delta = 6\%$, and the rates are divorced.

¹¹The shadow price of capital is simply the present value of the future stream of consumption benefits associated with £1 of private investment discounted at the SRTP. In the case of a 2 period project yielding benefits $B_t = [B_1, B_2]$ and a private investment yielding the rate of return on private capital, r , of 16% one year hence, then the consumption lost as a result of the public project as a result of the £1 displaced from the private project is £1.16. This is the shadow price of private capital and the public project is viable if the following inequality holds: $\frac{B_1}{1.06} + \frac{B_2}{(1.06)^2} \geq \frac{1.16}{1.06}$. This criteria differs from that in which simply the private rate of return on capital is used as the discount rate.

For example, in the ‘Green Book: Appraisal and Analysis in Central Government’, the UK government recommends the use of the social rate of time preference as the test discount rate for CBA (HM Treasury 2003). This rate is recommended for use across all departments, for all projects and is calculated to be $\delta = 3.5\%$ ¹². The policy in the US is more tailored. It is proposed that investments external to the government are evaluated at a rate reflecting the average return in the private sector, currently 7%. Alternatively, internal investments are evaluated at the rate of return on treasury bonds, 4%. The shadow price approach outlined above is also suggested for certain appraisals where the social rate of time preference is assumed to be reflected by the return on treasury bonds (Newell and Pizer 2001). The use of the rate of return on treasury bonds reflects the commonly held view that it is the risk free rate of return that is applicable to public investments. In any event, whatever the choice of SDR, usual practice is to employ the current estimate for all periods of time. One of the few exceptions to this rule is the U.K. government, which has recently introduced a declining schedule of discount rates to the Green Book for use in long-term projects (HM Treasury 2003)¹³.

Projects are appraised by establishing their Net Present Value (NPV) determined by summing up the net benefits that occur at each moment in time, where the net benefits are determined using accounting prices and are weighted by the *discount factor*;

$$a(t) = \exp\left(\int_0^t -\delta(s) ds\right) \quad (1.4)$$

which, reflects the value of the numeraire in each time period. As stated above, the discount *rate* is most frequently defined as the rate of change of the value of the numeraire or discount factor. However, there is a distinction to be made between average and marginal rates. The average rate of discount can be thought of as the rate which if applied constantly for all intervening years would yield the same present value as indicated by the discount factor. This rate can be derived for any time period from the simple rearrangement of (1.4):

$$\delta_a(t) = -\frac{1}{t} \ln a(t) \quad (1.5)$$

The marginal rate of discount is the period-to-period rate of change of the discount factor and can be calculated as follows:

¹²This is based upon the following figures: $\rho = 1\%$, $\theta = 1$ and $g = 2.5\%$. $\theta = 1$ when preferences were logarithmic for example.

¹³These policy changes came in response to previous reviews of the discounting literature (OXERA 2003).

$$\delta_m(t) = -\frac{\frac{\partial}{\partial t}a(t)}{a(t)} = -\frac{\dot{a}(t)}{a(t)} \quad (1.6)$$

It is common practice to assess the NPV of a project using a constant discount rate. Thus a partial equilibrium framework is implicitly assumed with the discount rate exogenous, the assumption being that the project is too small to influence the economy as a whole. Again, this accepted practice arises out of convenience and does not completely reflect the optimising economy outlined above, particularly for large projects. Clearly, where the discount rate is constant for all time periods, marginal and average rates coincide: $\delta_a = \delta_m = \delta$. However, where the discount rate is time dependent, for example, where we have declining discount rates (DDRs), this distinction can become important.

1.3 Declining Discount Rates in a Deterministic World

1.3.1 Growth (g) and consumption smoothing (θ)

The Ramsey rule in Equation (1.3) shows the determinants of the socially efficient equilibrium discount rate: pure impatience, ρ , the desire for consumption smoothing, θ , and growth, g . With certain knowledge of each of the parameters on the RHS of (1.3) the social rate of time preference, δ , is known with certainty, and in the competitive economy we know that it will be equal to the private and social return on capital. Given these consumption based determinants of δ , it is interesting to consider the its level and how it might change over time.

Firstly, as Dasgupta (2001) makes clear, given the definition of δ in (1.3), negative growth could, quite reasonably induce to negative social discount rates, particularly if one takes the view that $\rho = 0$ ¹⁴. Similarly, if growth is known to be declining then the discount rate will be declining. To add some form to this analysis we can see from the definition of δ ¹⁵:

$$\frac{\partial}{\partial t}\delta(t) = \frac{\partial\theta}{\partial t}g + \theta\frac{\partial g}{\partial t} \quad (1.7)$$

Hence, there are a number of situations in which the SDR will be declining in this deterministic setting. Firstly, if we maintain the assumption that $\theta > 0$ and constant over time ($\frac{\partial\theta}{\partial t} = 0$)

¹⁴This would not occur in the optimal Ramsey set up however since, for example, $f'(k) > 0$.

¹⁵We thank an anonymous referee for alerting us to this approach.

then DDRs will occur if growth is decreasing over time: $\frac{\partial g}{\partial t} < 0$ ¹⁶. A diminishing rate of growth is a very real possibility and may be particularly relevant when considering climate change prevention. With declining growth If this is the case then the appropriate discount rate for the long-term ought to be declining where $\frac{\partial \theta}{\partial t} = 0$. The point here is that projects which aim to avert climate change should no longer be considered in a partial equilibrium context (Dasgupta 2001). Clearly, the behaviour of the efficient discount rate over time is highly dependent upon the preferences of the representative household, in particular the level of θ and its evolution over time with changes in income. This is summarised in Proposition 1:

Proposition 1: Assuming that the pure rate of time preference is constant over time, in the deterministic case the socially efficient discount rate will decline unambiguously over time if, for whatever reason, growth is declining (increasing) $\frac{\partial g}{\partial t} < 0$ ($\frac{\partial g}{\partial t} > 0$) and preferences are such that $\theta > 0$ ($\theta < 0$) and θ is inversely related or unrelated to income, regardless of the level of growth, g .

Proof: The proof comes from inspection of the right hand side of (1.7). For the second term to be negative requires that where growth is decreasing, $\frac{\partial g}{\partial t} < 0$, (increasing, $\frac{\partial g}{\partial t} > 0$), θ must be positive (negative). For the first term to be non-positive requires that either i) $\frac{\partial \theta}{\partial t} = 0$, as in the example above; ii) $g > 0$ and $\frac{\partial \theta}{\partial t} < 0$; or iii) $g < 0$ and $\frac{\partial \theta}{\partial t} > 0$. Clearly in case i) if $\frac{\partial g}{\partial t} < 0$ ($\frac{\partial g}{\partial t} > 0$) then $\frac{\partial \theta}{\partial t} \delta < 0$ if $\theta > 0$ ($\theta < 0$). Case ii) and iii) are satisfied if preferences are such that θ is inversely related to income, making the *level* of growth unimportant.

Our first finding is that DDRs can emerge in a deterministic world because of predictable changes in the growth rate and associated changes in preferences for consumption smoothing or risk. Given that θ is mathematically equivalent to Pratt's coefficient of relative risk aversion, the preferences required for each of the cases above can be thought of as follows: Case i) requires preferences akin to constant relative risk aversion (CRRA), while cases ii) and iii) require preferences which are akin to decreasing relative risk aversion (DRRA). Clearly there exists a number of other cases in which DDRs may emerge where the first term and second

¹⁶That θ remains constant in the presence of positive or negative growth is akin to the commonly used modelling assumption that agents in the economy have constant relative risk aversion (CRRA). Clearly, this interpretation makes only partial sense in the deterministic case in which it is more sensible to talk of constant intertemporal substitution.

term are of opposite sign and yet their sum is still negative. In such cases the level of the parameters, θ , g , and their time derivatives are important. We do not isolate these conditions here. It suffices to note that growth, individual preferences and their behaviour over time are important determinants of the SDR in the deterministic case and that fluctuations in the discount rate used for discounting consumption equivalents can be a natural outcome of the traditional Ramsey model. The analysis here also provides a useful introduction to the work of Gollier (2002a, 2002b) which looks at the long-term discount rate under uncertainty. Under uncertainty the interpretation of θ as reflecting preferences for risk becomes more intuitive.

1.3.2 Environmental value and externalities

A second justification for DDRs in a deterministic world arises from the work of Weitzman (1994). It is well known that environmental externalities in consumption or production can cause the social and private rates of return on capital to diverge. Weitzman (1994) provides theoretical conditions for an ‘environmental’ SDR based upon the social rate of return to capital, which is lower than the private rate. In so doing Weitzman (1994) isolates the conditions under which DDRs emerge. His model incorporates two main ideas: society values environmental resources positively and the production of consumption goods can generate negative environmental externalities. These two basic tenets generate a tension between private investment and public investments in environmental protection, driving a wedge between the private and social rates of return. The model can be thought of as follows. If national income is either consumed, invested or diverted to environmental expenditures we can write:

$$Y(t) = f(k(t)) = C(t) + I(t) + \psi(t)$$

where $f(\cdot)$ is the production technology, $C(t)$ is consumption, $I(t)$ is gross investment and $\psi(t)$ is expenditure on reducing environmental damage, a social cost external to the production process. The relation between environmental expenditures and environmental damage as a proportion of income is defined as¹⁷:

$$\frac{D}{Y} = G\left(\frac{\psi}{Y}\right) \quad (1.8)$$

where $G_\psi < 0$ and $G_{\psi\psi} > 0$ ¹⁸. If investment is increased at time t by a marginal reduction

¹⁷ $G(\cdot)$ is assumed to be continuous and monotonic and is constant returns to scale.

¹⁸Where G_ψ and $G_{\psi\psi}$ are the first and second derivatives of $G(\cdot)$ with respect to ψ .

in consumption, keeping environmental expenditures constant, the private rate of return on capital can be thought of as:

$$\frac{\partial Y}{\partial k} = f'(k) \quad (1.9)$$

Hence the private rate of return, i , on capital, k , is equal to $f'(k)$. When production generates environmental externalities the social rate of return, r , will differ from the private rate. Rather than modelling the effect of environmental externalities directly, e.g. through explicit modelling of preferences for environmental resources, Weitzman imagines that environmental damage must be maintained at some initial level, \bar{D} . Given (1.8), this can only be achieved by a marginal increase in environmental expenditures, $\psi' = \frac{d\psi}{dY}$, diverted from each unit of incremental output, $\frac{\partial Y}{\partial k}$. Hence, the social rate of return on investment can be thought of as the rate of return in terms of output minus the rate of increase in expenditure required to maintain environmental standards:

$$r = \frac{\partial Y}{\partial k} - \psi' \frac{\partial Y}{\partial k} = i [1 - \psi'] \quad (1.10)$$

By taking the total derivative of (1.8) with respect to Y and solving for ψ' we are left with the term¹⁹:

$$r = i \left[1 - Z \left(1 + \frac{1}{E} \right) \right] \quad (1.11)$$

where $Z = \frac{\psi}{Y}$ and $E = -Z \frac{G_\psi}{G}$. The former is the proportion of national income spent on environmental clean-ups and the latter is the elasticity of environmental improvement (i.e. reducing D) with respect to environmental expenditure or the ease with which environmental damage can be reduced.

Notice that the social rate of discount, r , is lower than the private rate, i , for all positive levels of Z and E . For a given level of Z , when the elasticity is low, and environmental expenditures are ineffective at cleaning up environmental damage, this divergence is increased. Weitzman's interpretation, from the perspective of optimal growth, is that this is a signal that the economy is finding prior environmental damage difficult to undo and the solution might be to reduce growth. Alternatively, where the elasticity is high, a better solution might be to increase environmental expenditures (Weitzman 1994).

¹⁹The total derivative of $\bar{D} = YG(\frac{\psi}{Y})$ is: $0 = G(\cdot) + YG_\psi(\cdot) \left[\frac{\psi'}{Y} - \frac{\psi}{Y^2} \right]$. Rearranging this gives $\psi' = \frac{\psi}{Y} - \frac{G}{G_\psi}$.

The implications of this analysis for the discount rate are twofold. Firstly, under fairly general conditions, the existence of consumption externalities reduces the level of the social rate of return below the private rate. This is because society must divide the marginal return from investment between consumption and environmental protection. Secondly, the socially efficient discount rate will be declining over time if the proportion of income spent on environmental goods, Z , is increasing over time. With positive growth this is guaranteed if environmental resources are luxury goods. A similar result holds if the elasticity of environmental improvement is declining over time.

Changing values for the environment were the focus of earlier work on discount rates for environmental projects by Fisher and Krutilla (1975). They suggested that these evolving preferences could be simply captured by assuming that the marginal Willingness to Pay (WTP) or accounting price for the environment would change at some pre-determined rate, say α . WTP would then grow exponentially from some initial level WTP_0 such that $WTP_t = WTP_0 \exp(\alpha t)$. The present value of these environmental benefits at time t would then be equivalent to:

$$PV_{WTP} = WTP_0 \exp((\alpha - r)t) \quad (1.12)$$

where r is the SDR, which represents the rate of change in the accounting price for the numeraire. Fisher and Krutilla defined the ‘environmental’ discount rate as the net rate $\omega = r - \alpha$, suggesting that the change in the accounting price for the numeraire and environmental goods can be captured by this net discount rate. This net rate is constant over time and captures a prediction about the evolution of values from WTP_0 .

One example of the mechanism for this process is to assume that the increase in WTP is driven by income growth such that $\alpha = \varepsilon g$, where g is the growth of income and ε is the income elasticity of WTP (Gravelle and Smith 2000). Both Krutilla and Fisher (1975) and Horowitz (2002) reflect on the effect of resource scarcity on WTP for environmental goods in this framework. Both perspectives provide arguments for increasing WTP for environmental goods and hence a reduction in the level of the (time invariant) discount rate for the relevant benefit or cost²⁰.

The conditions under which DDRs emerge differ from those of Weitzman (1994). In the Fisher and Krutilla model if the proportion of income spent on environmental goods is increas-

²⁰Gravelle and Rees (2000) focus on health benefits for example.

ing, i.e. growth is positive and environmental goods are luxuries ($g > 0$, $\varepsilon > 1$), then the environmental discount rate should be lower than r , yet constant over time. DDRs emerge from the Fisher and Krutilla analysis if the parameters which define the evolution of WTP (α) are changing over time²¹. Furthermore, whereas Fisher and Krutilla's discount rate applies solely to environmental costs and benefits, Weitzman's presumably applies to all costs and benefits. The former has become known in the literature as a 'dual discounting' approach, since it refers to discounting different costs and benefits at different rates, and has received considerable attention in climate change modelling (Tol 2004, Yang 2004).

Both Weitzman (1994) and Fisher and Krutilla (1975) have been criticised on a number of counts. In many ways Weitzman's environmental discount rate is difficult to interpret in light of the reduced form set up and, in particular, the absence of an explicit modelling of preferences, environmental goods and externalities. The assumption that some arbitrary environmental standard, \bar{D} , must be maintained captures these effects but makes the subtraction of environmental expenditures from the private rate of return in (1.10) rather ad hoc. More generally, it is thought that deriving the 'effective' or 'environmental' discount rate using (1.12) or other dual discounting techniques, and using this as the SDR obscures several issues (e.g. Arrow et al 1995, Horowitz 2002). As can be seen from the discussion of the Ramsey equation (1.3), there is a completely different set of assumptions that connect the social rate of return to capital, r , growth, g , and preferences (e.g. for the environment, ε). The discount rate is a poor vehicle for capturing these various factors and in the long-term doing so implies a number of very strong structural assumptions. A more widely accepted alternative is to apply the time invariant SDR, e.g. r , to benefits and costs evaluated in consumption equivalents which reflect the evolution of WTP through time. This disentangles issues of evolving values for the environment from issues of discounting and 'does not change the discount rate to apply to the consumption stream' (Arrow et al 1995)²².

1.3.3 Limitations of the financial markets

One of the fundamental assumptions underlying the use of discounting in cost benefit analysis is that the potential exists for the transfer of resources across generations. That is, the use

²¹Horowitz (2002) for example appears to confuse Weitzman (1994) and Fisher and Krutilla (1975) in this sense.

²²Preliminary work by Traeger (2004) shows that this widely held view may not be true where there is limited substitutability between environmental and produced goods in the utility function.

of the discount rate, e.g. r , to evaluate a project implies that funds could alternatively earn that rate of return in the economy. When considering the long run this implies the existence of a mechanism to facilitate intergenerational transfers of these alternative returns (Lind 1995). There are a number of reasons why this assumption can be called into question. Firstly, financial markets only cover the relative short term, with assets having maturities limited to about 30-40 years. Secondly, although it is possible for investments to be rolled over as and when they mature and there are numerous fiscal and other policies which can redistribute assets across generations (Bradford 1999), it is not clear that governments will be able credibly to commit to such a course of action (Arrow 1999). Some authors suggest that these facts alone provide some further justification for DDRs.

Rabl (1996), for example, effectively interprets ρ in (1.3) as the inequality aversion parameter for the current generation and the term θg as the inter-generational inequality aversion parameter. Since financial markets cover only a limited duration, he argues, the duration over which the current generation can redistribute its wealth through time is limited. Hence, ρ should be excluded from estimates of the discount rate for horizons greater than those reflected by the financial markets. He suggests that the SDR should be the social rate of time preference as measured by $\rho + \theta g$ within the duration of financial assets and θg thereafter. This captures the idea that θg represents real growth in the future: real resources for future generations which is not directly constrained by the financial markets. This results in a declining 'stepped' schedule for discount rates. Rabl's interpretation does not represent an attempt to determine the efficient discount rate and is rather ad hoc. It does, however, raise the questions concerning the assumptions underlying discounting in CBA, that is, the existence of intergenerational transfers.

Indeed, it is perhaps the fact that we are uncertain about the long-run market rate of return that the social rate of time preference is frequently used for CBA. In other words, rather than looking to financial markets for answers concerning the correct discount rate for the long-run, perhaps the economic arguments associated with the consumption based determinants of the discount rate will be more fruitful.

1.4 Declining Discount Rates in an Uncertain World

When uncertainty with regard to the determinants of the discount rate is introduced to the analysis the case for DDRs is even more compelling and much of the recent debate concerning DDRs has centred upon the analysis of uncertainty concerning future states of the world, in particular the social rate of return to capital, r , (e.g. Weitzman 1998), and growth, g (e.g. Gollier 2002a, 2002b, 2004b). In particular, just as Weitzman (1994) introduced preferences for environmental goods as a determinant of the SDR, Gollier shows that in an uncertain world preferences for risk are important.

1.4.1 Uncertainty about the social rate of return (r)

Weitzman (1998) developed ideas first formalised by Dybvig et al (1996) and shows how uncertainty regarding the interest rate, r , leads to DDRs²³. Clearly, there are good reasons to expect that r is uncertain in the long-run. For example, there is uncertainty concerning capital accumulation, the degree of diminishing returns, the state of the environment, the state of international relations, and the level and pace of technological progress. Dybvig et al (1996) showed that when there is currently uncertainty about the short-term interest rate, the discount rate that should be applied to extremely distant time periods, strictly as $t \rightarrow \infty$, is the lowest rate with a positive probability of being realised. A proof of this is shown in Appendix 1. This argument suggests lower socially efficient discount rates at the limit, but says nothing about the path of these rates over time: i.e. the shape of the yield curve²⁴. Weitzman (1998) went on to show the relationship between the socially efficient discount rates and the time horizon. He shows that, when agents wish to maximise the expected NPV in choosing between an investment at an uncertain per-period risk free interest rate, \tilde{r} , or in a project that yields a sure benefit in period t , the socially efficient discount rate (before the realisation of the uncertain risk free rate) is declining with time. In other words, the yield curve is declining. In order to understand these results we derive Weitzman's *certainty equivalent discount rate*, show a proof that the limit of this discount rate as $t \rightarrow \infty$ is the lowest possible value and provide a numerical example.

With certain discount rates the discount factor is given by $a(t)$ as shown in equation (1.4)

²³Similar ideas have been expressed in Sozou (1998) and Azfar (1999).

²⁴The yield curve shows the term structure of financial assets, that is, how the rate of return varies for assets with different maturities.

above. When the social rate of return is uncertain however, there are numerous potential states of the world, each with an associated discount factor and probability of realisation. If there are j states of the world then the discount factor at time t associated with each is:

$$a_j(t) = \exp\left(-\int_0^t r_j(s) ds\right) \quad (1.13)$$

where it is assumed here that the interest rate can be a function of time: $r(t)$. Given uncertain future discount rates it becomes necessary to derive a summary measure of the discount factor and discount rate. Weitzman uses certainty equivalent analysis for risk-neutral agents and defines the *certainty equivalent discount factor* (CEDF) as the expectation of the discount factor. From this he derives the *certainty equivalent discount rate* (CER)²⁵. Supposing that each potential discount rate r_j is realised with probability p_j , such that $\sum p_j = 1$ and $r_j \in [r_{\min}, r_{\max}]$ ($j = 1, \dots, n$). The certainty equivalent discount factor for a risk neutral agent is defined as²⁶:

$$A(t) = E\left[\exp\left(-\int_0^t \tilde{r}_j(s) ds\right)\right] = \sum_j p_j a_j(t) \quad (1.14)$$

From this it is possible to define both the average and marginal certainty equivalent discount rates at time t , corresponding to the definitions in Section 1.2: r_a^{CER} and r_m^{CER} respectively:

$$\exp(-r_a^{CER}(t)t) = A(t) \quad (1.15)$$

which implies:

$$r_a^{CER}(t) = -\frac{1}{t} \ln[A(t)] \quad (1.16)$$

whereas:

$$r_m^{CER}(t) = -\frac{\frac{\partial}{\partial t} A(t)}{A(t)} \quad (1.17)$$

²⁵This is not crucial for this particular result to hold but is important for ease of exposition. The certainty equivalents could be defined to incorporate higher moments of the distribution of discount rates and to reflect risk aversion, but with a loss of tractability.

²⁶Note that the probability densities are assumed to be time invariant. This is not necessary for the result but as we shall see later, the nature of the probability distribution is of considerable importance for any estimated schedule of certainty equivalent discount rates.

The former is the rate of discount that if applied in every period from 0 to t would yield the same value as the expected discount factor at time t . The latter is the instantaneous, period-to-period rate²⁷. Weitzman (1998) works with r_m^{CER} , noting that at the limit, as $t \rightarrow \infty$, they are precisely the same, and shows that r_m^{CER} declines continuously and monotonically over time and that its limit as $t \rightarrow \infty$ is r_{\min} . More generally, Gollier (2002b) shows that an arbitrage exists if, prior to realisation of r , (1.15) does not hold. That is, thinking of the right hand side of (1.15) as the (uncertain) price of a claim to £1 at time t discounted using the certainty equivalent discount factor, and the left hand side as the present value of the benefit, it is clear that in equilibrium both sides must be equal. Hence, the certainty equivalent discount rate is the equilibrium socially efficient rate for risk neutral agents prior to the realisation of \tilde{r} ²⁸.

The mechanics of Weitzman's results are as follows. From (2.1) and (1.17) it is easy to show that the certainty equivalent marginal rate can be written as a weighted average of the potential realisations of r :

$$r_m^{CER} = \sum_j w_j(t) r_j \quad (1.18)$$

where the weights in this case are simply: $w_j(t) = p_j a_j(t) / \sum p_j a_j(t)$ and $\sum w_j(t) = 1$. Taking the derivative of this with respect to time we obtain:

$$\frac{d}{dt} r_m^{CER} = \sum_j \dot{w}_j(t) r_j = - \sum_j w_j(t) (r_j - r_m^{CER})^2 \quad (1.19)$$

which is clearly negative²⁹. That the limit of $\lim_{t \rightarrow \infty} r_m^{CER} = r_{\min}$ comes from noticing that,

²⁷It is the definition of the average certainty equivalent rate in Equation (1.16) that has lead some commentators to describe Weitzman's CER as a restatement of Jensen's inequality since it effectively defines r_a^{CER} as the harmonic mean of $\exp(-r_j t)$ (Newell and Pizer 2001). For example, if there are two possible interest rates with associated probabilities (r_1, r_2) and (p_1, p_2) respectively then $\exp(r_a^{CER} t) = \frac{\exp(r_1 t) \exp(r_2 t)}{p_1 \exp(r_2 t) + p_2 \exp(r_1 t)}$, which is a weighted harmonic mean of $\exp(r_1 t)$ and $\exp(r_2 t)$. This definition is strictly different to Weitzman's which is effectively a weighted arithmetic mean.

²⁸Another way to think about this is so say that, in the face of uncertain r , agents are unsure as to how to evaluate the opportunity cost of the project, and hence which discount factor to employ in determining the NPV. This is equivalent to stating that if agents desired a sure benefit of £1 at time t , then given that they face an uncertain discount factor before the realisation of \tilde{r} , they are uncertain of the contribution they should make (Gollier 2002a). Agents must make some judgement of the discount factor and will use the certainty equivalent discount factor.

²⁹The last step is not entirely obvious, so we elaborate. Dropping the m subscript from r_m^{CER} , note that:

$\dot{w}_j(t) = w_j(t) (\sum w_i(t) r_i - r_j) = w_j(t) (r^{CER} - r_j)$, therefore $\frac{d}{dt} r^{CER} = \sum w_j(t) (r^{CER} r_j - r_j^2) = (r^{CER})^2 -$

where $r_1 = r_{\min}$:

$$\lim_{t \rightarrow \infty} \frac{w_j(t)}{w_1(t)} = 0$$

which means that as $t \rightarrow \infty$ the weights associated with all but the lowest discount rate tend to zero due to the presence of $a_j(t)$, and yet, since $\sum w_j(t) = 1$, the weight for the lowest discount rate, $w_1(t)$, must tend towards 1³⁰. The intuition behind this is that since the weights for each realisation ($w_j(t)$) contain the discount factors $a_j(t)$, in scenarios with higher discount rates the discount factors decline more rapidly to zero. As such, the weight placed on scenarios with high discount rates itself declines with time, until the only relevant scenario is that with the lowest conceivable interest rate. In effect, the power of exponential discounting reduces the importance of future scenarios with high discount rates to zero, since the discount factor in these scenarios goes to zero. Since in the ex ante equilibrium the certainty equivalent rate of discount must equal the socially efficient discount rate in all periods of time, this results in a SDR which declines over time.

Numerical Example of Weitzman's CER: Appendix 2 works through an explicit example of Weitzman's certainty equivalent discount rate. Table 1.1 shows the resulting schedule of marginal and average discount rates over continuous time assuming that $(r_1, r_2) = (5\%, 2\%)$ and $(p_1, p_2) = (0.5, 0.5)$. Table 1.1 reflects the aspects of the certainty equivalent discount rate described above. Both the average and the marginal certainty equivalent rates are declining monotonically through time while approaching the lowest possible realisation in the long-run: $r_{\min} = 2\%$.

1.4.2 The need for an analysis of preferences

Weitzman's argument seems very convincing: uncertainty in the discount rate itself leads to an arbitrage in which the socially efficient discount rate is a declining function of time. In addition, the apparent ease of application renders it appealing to the practitioner (see Appendix 2).

However, Gollier (2004a) argues that Weitzman's logic relies critically upon a tacit assumption

$\sum w_j(t) r_j^2$. This term is equal to that obtained by multiplying out (1.19). That is, noting that $\sum w_j(t) = 1$ we get: $-\sum w_j(t) (r_j^2 + (r^{CER})^2 - 2r_j r^{CER}) = 2(r^{CER})^2 - (r^{CER})^2 - \sum w_j(t) r_j^2$ and we are done.

³⁰ Gollier (2002a) provides an elegant proof of the following: $\lim_{t \rightarrow \infty} r_a^{CER} = r_{\min}$, i.e. for the averager CER, by appeal to Pratt's Theorem.

	Year (t)				
	10	50	100	200	500
Discount factor ($a_1(t)$)	0.819	0.368	0.135	0.018	0.000
Discount factor ($a_2(t)$)	0.607	0.082	0.007	0.000	0.000
CEDF ($A(t)$)	0.713	0.225	0.071	0.009	0.000
Marginal CER (r_m^{CER})	3.277%	2.547%	2.142%	2.007%	2.000%
Average CER (r_a^{CER})	3.388%	2.983%	2.645%	2.345%	2.139%

Table 1.1: Numerical Example of Weitzman's Certainty Equivalent Rate

that the current generation should bear the risk of variation in the SDR. He illustrates this point by using the opposite assumption.

Weitzman's certainty equivalent rate defines the discount rate that should be used when the objective is to maximise the Expected Net Present Value (ENPV) of investments given uncertainty in the interest rate. For example, an agent may wish to compare the return to an investment of £1 with fixed future benefit, say £ Z in year T , to an alternative investment with a random rate of return, \tilde{r} . She ranks these alternatives by calculating the ENPV. Following Gollier (2004a) in such a case the ENPV rule can be represented by:

$$ENPV : ZE[\exp(-\tilde{r}T)] - 1 \geq 0 \quad (1.20)$$

If this condition holds, then the agent should proceed with the project. Given that maximising ENPV is the objective, and using (1.16), the (average) certainty equivalent per period discount rate in this environment can be defined as r^{PV} :

$$\exp(-r^{PV}t) = E[\exp(-\tilde{r}t)] \implies r^{PV} = -\frac{1}{t} \ln[E[\exp(-\tilde{r}t)]] \quad (1.21)$$

which is declining over time (t) as described above.

Alternatively, imagine that we want to maximise the expected net future value (ENFV), i.e. we wish to rank our projects on the basis of maximising the value of assets that accumulate to future generations. The ENFV rule can be thought of as:

$$ENFV : Z - E[\exp(\tilde{r}T)] \geq 0 \quad (1.22)$$

In this case the certainty equivalent per period interest rate, r^{FV} , that produces the same outcome as the random interest rate is that which satisfies:

$$\exp(r^{FV}t) = E[\exp(\tilde{r}t)] \implies r^{FV} = \frac{1}{t} \ln[E[\exp(\tilde{r}t)]] \quad (1.23)$$

Clearly, $r^{PV} \neq r^{FV}$. Furthermore, r^{FV} it is easy to show that the latter is increasing over time. Hence, Gollier claims, when we rank projects by ENFV the socially efficient discount/interest rate, is in fact increasing over time. The arguments shown above can be used to show somewhat symmetrically, that r^{FV} converges to the highest possible value of \tilde{r} as $t \rightarrow \infty$.

So, confusingly, whereas in the absence of uncertainty the two decision criteria are equivalent, once uncertainty regarding the discount rate is introduced the appropriate discount rate for use in CBA depends upon whether we choose ENPV or ENFV as our decision criterion. In the former case discount rates are declining and in the latter they are rising through time. Which of these criteria is preferable?

Gollier (2004a) explains that the two criteria differ in their temporal allocation of residual risk. Using ENPV implies that the present generation (strictly, $t = 0$) bears the risk. This is because, once the discount rate is realised (r) the NPV may or may not be positive. Since the payoff in the future (Z) is certain, any residual losses are borne by the present generation. It is as if they have a secure payoff for future generations but a random payment in the present (Gollier 2002a). For example, if the ENPV equalled zero, but the realised discount rate is greater than the certainty equivalent rate: $r > r^{PV}$, the project is not viable ex post, and investors must internalise the opportunity cost. The symmetric argument to this is the case where $ENPV < 0$ and $r < r^{PV}$. However, using ENFV implies that future generations bear the risk. The present generation makes a certain contribution to the project ($\mathcal{L}1$), but the rate at which the fund accumulates, and hence the outcome in the future ($\exp(\tilde{r}T)$), is uncertain before the realisation of \tilde{r} . Any shortfall is borne by the future.

Consequently, so the argument goes, choosing between these two decision criteria under uncertainty appears to be solely a question of the temporal allocation of risk. Given the risk neutral environment we cannot appeal to risk preferences in order to make this decision. Gollier argues that economic theory provides no guidance in the Weitzman set-up since current and future preferences for risk are effectively assumed away. However, the financial literature concerning the yield curve is replete with such considerations and in a number of subsequent papers Gollier returns to this literature to describe the role of risk preferences in determining

DDRs (Gollier 2002a, 2002b, 2004b). The following Section describes these contributions.

1.4.3 The effect of uncertain growth (g) on the Social Time Preference Rate (δ)

In a deterministic world we noted that there are two underlying characteristics of individual preferences which determine the social rate of time preference, δ ; i) pure impatience, ρ , and ii) the desire to smooth growing wealth over time, θ . In a competitive equilibrium individual preferences to discount the future are balanced against the risk-free market rate of return, r . The marginal benefits of consumption and saving are equated. Where there are frictionless financial markets, if the risk free rate of return determined in this way is used as the test discount rate for public projects the result will be an optimal level of investment (Gollier 2002a).

The difficulty for the long run is the absence of financial assets whose maturity extends to the horizon associated with the new types of projects and policies that the government is faced with, e.g. global warming. Government bonds, for example, do not extend beyond 40 years in general. In the absence of a measure of the long run discount rate determined by financial markets, Gollier (2002a, 2002b) turns to economic theory to provide some answers. In doing so he provides a potential solution to the conundrum encountered above concerning the temporal allocation of risk in the risk neutral environment of Weitzman. The question of whether agents in the present or the future should bear the risk associated with investment decisions is answered by reference to individual preferences for risk, their evolution over time and the analysis of the social rate of time preference, δ .

Gollier uses the framework of a ‘tree economy’ (Lucas 1978) in which growth is uncertain and represented by \tilde{g} in order to look at the determinants of the equilibrium interest rate³¹. The growth rate of the economy is taken as the ‘primal’ of the model rather than the risk free rate itself, as in the case of Weitzman (1998). As in Section 1.2, agents make saving and consumption decisions to maximise their expected utility, $E[u(c)]$, in each period of time, t , given their expectation of future growth. Following Gollier we illustrate the arguments in

³¹The tree economy describes a situation in which each individual is endowed with some productive capital, a tree, with uncertain exogenous growth rate, g , in the form of fruits. The fruits are perishable and therefore borrowing and lending occurs within periods with debts repaid by growth in future periods. In effect, therefore, capital is exogenous, and the interest rate that sustains the equilibrium is determined by individual characteristics that make up δ .

discrete time. The first order condition for expected utility maximisation provide us with the determinants of the short-term risk free interest rate, $r(c)$, in this economy and can be written as:

$$1 + r(c_t) = \frac{u'(c_t)}{\beta E[u'(c_t(1 + \tilde{g}_{t+1}))]} \quad (1.24)$$

See Appendix 3 for the derivation. Equation (1.24) says that utility maximising individuals will equate the ratio of current and future expected marginal utility to the short term (gross) interest rate, where future utility is discounted by the rate of pure time preference, that is $\beta = \frac{1}{\rho} - 1$. There is no productive sector in this model, therefore the risk-free rate represents the preference-based determinants of the discount rate.

The effect of certain growth upon the short term risk free rate has been described above. Gollier extends this analysis to describe the effect of uncertain growth on the short and long-term behaviour of the discount rate. One point is immediately clear. Uncertainty in growth will reduce the discount rate when the marginal utility of consumption is convex, in which case Jensen's inequality holds: $E[u'(c(1 + g_{t+1}))] \geq u'(E[c_t(1 + g_{t+1})])$. This introduces another economic reason why individuals discount the future. Faced with uncertainty about future income levels, individuals will value additional units of consumption in the future and will save for precautionary reasons, resulting in a reduced risk free rate (Kimball 1990, Gollier 2001).

To recap, there are now three main characteristics of individual preferences that determine the risk free rate: 1) pure time preference, ρ . 2) the wealth effect reflected by, θ , and 3) precaution: the desire to engage in precautionary saving in the face of uncertain income growth. The latter is reflected in the degree of convexity of marginal utility of consumption and hence is dependent upon the third derivative of utility. Individuals are said to be prudent when marginal utility is convex: $u'''(.) > 0$ (Kimball 1990).

In order to quantify the effects of these different determinants of the discount rate it is useful to augment the Ramsey rule. Appendix 3 shows that the associated expression for the risk free rate under uncertainty is:

$$r = \rho + \theta E[g_{t+1}] - 0.5 \text{var}[g_{t+1}] \theta P(c) \quad (1.25)$$

Determinants 1)-3) are represented on the RHS of (1.25) respectively. The term $P(c) = \frac{u'''}{u''} y$ is a measure of *relative prudence* and is distinct from preferences for consumption smoothing

and risk aversion which is reflected once more by θ (Kimball 1990). Hence, economic theory states that the equilibrium risk free rate is decreased under uncertain growth when agents are ‘prudent’ (when $u''' > 0$), and increased by the desire to smooth growing consumption over time. Consequently, the overall effect depends upon the balance between the prudence effect (the third element) and the wealth effect (the second element).

Equation (1.25) represents the short-term risk free rate: e.g. the return at t of a bond that yields a cash flow at time $t + 1$. However, the thrust of this discussion concerns the nature of the long-run risk free rate for use in CBA. The analysis can be extended to the long-run in a fairly straightforward manner. The per-period rate of return evaluated at time t of an asset which matures at time $t + n$, can be defined as a simple extension of equation (1.25):

$$(1 + r_{ct})^n = \frac{u'(c_t)}{\beta^n E \left[u' \left(c_t \prod_{t+1}^{t+n} (1 + \tilde{g}_{t+1}) \right) \right]} \quad (1.26)$$

where the denominator represents the value of marginal utility at time given the expected accumulation of growth between t and $t + n$. Notice that when $n = 1$, equation (1.26) is the same as equation (1.24). Equation (1.26) effectively characterises the yield curve: the plot of the term structure against time. This is naturally of interest since it tells us the discount rate that should be applied in CBA for costs and benefits that occur at each date.

In general, the interest rate will depend upon the maturity. For example, it is well known that if agents in period t expect growth in period to be significantly lower (higher) than growth in period $t + 1$, then the yield curve will be downward (upward) sloping. This can be deduced from equation (1.26). This outcome is analogous to the discussion concerning deterministic growth in Section 1.3. However, in order to control for these effects, Gollier (2002a) undertakes his analysis in a context in which growth is expected to be similar across periods. The shape of the yield curve then depends upon the nature of the preferences held by individuals and the subsequent temporal balance between wealth effects and prudence effects.

Gollier (2001, 2002a, 2002b) presents several results of interest. Firstly, when individuals display Constant Relative Risk Aversion (CRRA) the yield curve is flat and the prudence and wealth effects exactly compensate one another. This corresponds to the conventional situation in which the discount rate for CBA remains constant for all time. Secondly, when it is assumed that there is no possibility of recession in the future, and individuals display Decreasing Relative Risk Aversion (DRRA), the yield curve is downward sloping. Then the risk free rate is declining

over time and thus the discount rate for CBA declines over the time horizon of the project. Lastly, when the prospect of recession is introduced the conditions for a declining yield curve become highly specialised. For example, if there is only a risk of recession in the long run, the yield curve is declining only if individuals display both DRRA *and* Increasing Absolute Prudence (IAP). This means that $P'(c) > 0$ (there are a number of additional necessary conditions for this to hold - for details see Gollier (2002b)). This represents a distinct class of utility functions with restrictions upon 4th derivatives. Furthermore, if the risk of recession is extended to all future periods, short-run and long run, a declining yield curve requires restrictions on the 5th derivatives of the utility function. As Gollier himself states, there is little hope that such conditions can be tested in the near future.

The complexity of the analysis is dependent upon the assumptions concerning the probability distribution of growth and the inter-temporal relationships. For the purpose of the analysis above Gollier (2002a, 2002b) assumes that the growth shocks are independently and identically distributed. Although this is unrealistic, it avoids the complications associated with the analysis of serially correlated shocks. In more recent work, Gollier (2004b) provides an analysis of the long-term discount rate in which these assumptions concerning serial correlation are relaxed. He finds that where there is positive correlation between the expected value of future growth and the short term growth rate, a downward sloping yield curve requires only that the representative agent is prudent, that is $u'''(.) > 0$. Clearly these conditions on preferences are less restrictive than in the *i.i.d* case assumed above. A number of other results are presented for different assumptions concerning the serial correlation of growth rates. One interesting example allows for a stochastic process which switches randomly between high and low growth regimes with Poission events. Another reflects the approach of Weitzman (2004) and includes Bayesian learning as the source of positive serial correlation. In both cases, DDRs emerge if the representative agent has CRRA preferences. Furthermore, the declining schedule is more rapid with positive serial correlation of growht rates than without.

Gollier's analysis provides some potentially testable propositions, which draw directly from expected utility theory. The formal economic foundation for the determination of long-term discount rates avoids the *ad hoc* adjustments of the discount rate common in the literature. Furthermore, the explicit treatment of risk is potentially more general than the risk neutral environment of Weitzman (1998). This approach is indeed technical and complicated, and the preferences that lead to DDRs are frequently difficult to test, but as Gollier (2004a) notes:

‘this is probably the cost to be paid to make policy recommendations that make economic sense’ (Gollier 2004a, p5)

Not only are preferences of great importance here, the recent contributions to this area emphasise the importance of the assumptions concerning the distribution of random growth within and between periods. Moreover, we should remain open to the prospect that preferences and stochastic processes in society are such that the socially efficient discount rate could be decreasing, constant or increasing over time.

1.5 Intergenerational Equity and Sustainability

The foregoing has concerned itself with the analysis of the efficient discount rate and its behaviour over time without any real discussion about the implications for inter-generational equity and sustainability. In this Section we discuss the contributions which take sustainable growth and inter-generational equity as their departure point. The main focus of the discussion is on the important contributions of Chichilnisky (1996, 1997) and Li and Löfgren (2000), both of which explicitly introduce the notions of intergenerational equity and sustainability. Each paper models optimal sustainable economic growth and each is concerned with deriving the welfare effects of growth paths which are sustainable in the sense that they satisfy particular axioms with regard to intergenerational equity. The axioms employed imply social preferences which are ‘sustainable’ or ‘intertemporally equitable’. Welfare is measured in terms of the utility of a social planner and, with utility as their numeraire, the discussion of discount rates concerns the utility discount rate, ρ , rather than the social rate of time preference, δ , or the social rate of return, r . Both contributions show that a declining utility discount rate is consistent with a rule whereby current (future) generations must always take into account the well-being of future (current) generations. That is, there must be no ‘dictatorship’ of one generation over another. In this way what Chichilnisky (1997) refers to as the ‘tyranny of the present over the future’ associated with constant rate discounting is overcome.

Chichilnisky (1997) introduces two axioms for sustainable development³². She also characterises the preferences that satisfy these axioms. The axioms require that the ranking of alternative consumption paths is sensitive not only to what happens in the present and immediate future, but also to what happens in the very long run. Sensitivity to the present means

³²A discussion of this model is also found in Heal (1998).

that there is no date before which events are given zero weight. Sensitivity to the long-run future means that there is no date where changes after that date do not matter, in the sense of affecting the ranking. Chichilnisky's criterion can be represented in the following objective function:

$$\max_{c,s} \pi \int_0^{\infty} u(c(t), s(t)) \exp(-\rho t) dt + (1 - \pi) \lim_{t \rightarrow \infty} u(c(t), q(t)) \quad (1.27)$$

Instantaneous utility $u(\cdot)$ is a function of consumption (c) and the resource stock (s) at each time period (t), while $\exp(-\rho t)$ is the conventional exponential utility discount factor. $u(\cdot)$ is assumed to be the same for all dates so that generations are assumed to be the same in the way they rank alternatives.

Intuitively, the limit term reflects the sustainable utility level attained by a particular policy decision regarding $c(t)$ and $s(t)$. This can be interpreted as the well-being of generations in the far distant future. Chichilnisky's approach is a mixture of the two approaches seen so far: a generalisation of the discounted utilitarian approach, mixed with an approach that ranks paths of consumption and natural resource use according to their long-run characteristics, or sustainable utility levels. This criterion can be applied under the two main axioms regarding the ranking of alternative utility paths. Notice that $\pi \in [0, 1]$, can be interpreted as the weight that the decision maker applies to each component of the criterion, with π providing the weight given to the present generation, and $(1 - \pi)$ representing the weight placed upon the future generation.

However, Dasgupta (2001) has criticized this approach on the basis that there is a way in which all generations can have their cake and eat it too. Suppose the current generation devises a plan that maximizes only the integral part of the maximand in equation (1.27). It simultaneously announces its intention to abandon that plan at some date in the distant future, at which point it will switch to a plan that then maximizes only the asymptotic part of the maximand. The farther this switching date is in the future, the more nearly the integral part will be maximized. But there will always be an infinite number of dates after the currently planned switching date, and hence it will always be possible to increase welfare by postponing the switching date.

In contrast to Chichilnisky (1997) who treats present and future generations as separate entities in the objective function of the decision maker, Li and Löfgren (2000) treat the future differently. Li and Löfgren assume society consists of two individuals, a utilitarian and a

conservationist, each of which makes decisions over the inter-temporal allocation of resources. The utility functions of these two individuals are identical, and again have consumption and the resource stock as their arguments. The objective function employed by Li and Löfgren is:

$$\max U = \pi U_1 + (1 - \pi) U_2 = \int_0^\infty u(c(t), s(t)) D(t) dt \quad (1.28)$$

where,

$$U_1 = \int_0^\infty u(c(t), s(t)) \exp(-\rho_U t) dt \quad (1.29)$$

$$U_2 = \lim_{\rho_C \rightarrow 0} \int_0^\infty u(c(t), s(t)) \exp(-\rho_C t) dt \quad (1.30)$$

where $D(t)$ is the discount factor. The important difference between these two decision makers is that they are assumed to discount future utilities at different rates. The utilitarian, who wants to maximise the present value of his utility (U_1), has a rate of time preference equal to ρ_U . The conservationist, who derives utility from conserving the stock of the natural resource, has a rate of time preference equal to ρ_C and maximises his utility. The overall societal objective is to maximise a weighted sum of wellbeing for both members of the society, given their different respective weights upon future generations. The effective utility discount rate in Li and Löfgren is given by³³:

$$\rho(t) = -\frac{1}{t} \ln \{ (1 - \pi) \exp(-\rho_C t) + \pi \exp(-\rho_U t) \} \quad (1.31)$$

A time profile of discount rates can therefore be found by merely selecting the discount rates for the conservationist and the utilitarian, ρ_C and ρ_U respectively. For example, if the conservationist discounts the future at a rate of zero: $\rho_C = 0$, the discount factor becomes:

$$D(t) = (1 - \pi) + \pi \exp(-\rho_U t) \quad (1.32)$$

In the distant future when t is large, (1.32) has a minimum value of $(1 - \pi)$, the weight attached to the conservationist, or future generations. It is in this way that the effective discount rate can be thought of as declining over time to zero. Thus, unlike the utilitarian discount function, which tends to zero as time reaches towards infinity, the weighted discount

³³It is interesting to note the mathematical equivalence of (1.31) with the average certainty equivalent rate defined in (1.16). π represents an intergenerational weight here rather than a probability in (1.16).

function tends to the weight for the far distant future. Hence Li and Löfgren's model results in a positive welfare weight for the conservationist and there is no dictatorship of present over future generations. As the utilitarian's welfare level is explicitly considered, there will also not be any dictatorship of the future over the present. Thus, the model explicitly considers intergenerational equity. Within this framework, the conservationist will dominate the far-distant future. Therefore the discount rate will be a declining function of the time horizon.

1.6 Arguments from Behavioural Economics

We have seen some of the normative and theoretical arguments for DDRs in the discussion above. In this Section we concern ourselves with the considerable empirical and experimental evidence of how individuals discount time.

1.6.1 Evidence of hyperbolic discounting

Over the last couple of decades, increasing evidence from experiments conducted by economists and psychologists in the lab and the field suggests that people use a declining discount rate in making intertemporal choices. Researchers typically ask subjects to choose between a set of delayed rewards, and construct the shape of the discount function from their responses. Harris and Laibson (2001) note that a large number of such experiments has been conducted, with a variety of rewards such as money, durable goods, sweets, relief from noise and so on³⁴. The results from these experiments suggest quite strongly that the discount rate applying to consumption trade-offs in the present is higher than that applying to trade-offs in the future. In other words, individuals are more sensitive to a given time delay if it occurs closer to the present than if it occurs farther in the future.

There are some dissenting voices, however. Read (2001) and Rubinstein (2003) offer other interpretations of the empirical evidence. Rubinstein (2003) presents his own experimental evidence that is not consistent with either constant or hyperbolic discounting, but is consistent with a decision-making procedure based on *similarity relations*³⁵. This procedure assumes that individuals ignore small differences and focus on large differences when comparing two alternatives. Read (2001) argues that the so-called evidence of hyperbolic discounting is in

³⁴See, for instance, Thaler (1981), Cropper et al. (1994), Kirby (1997) and the review by Ainslie (1992).

³⁵Preliminary results from unfinished work by Benhabib et al. (2004) is also suggestive of alternative explanations.

fact evidence of *sub-additive discounting*, where discounting over a given period is greater when the period is divided into subintervals than when it is left undivided. This implies an inverse relationship between the discount rate and the size of the delay. In other words, Read (2001) argues that the discount rate is not a function of relative location in time, as proponents of hyperbolic discounting suggest, but is rather a function of the size of the time delay. Finally, Mulligan (1996) argues against hyperbolic discounting on the basis that hyperbolic discounters leave themselves open to exploitation on the markets by ‘Dutch books’. People with that tendency, he argues, would rapidly learn to correct their ways. While this logic might hold on futures markets, we would doubt that hyperbolic discounting at an individual day-to-day level would be damaging enough for people to modify their behaviour.

So although the jury is still out on the precise explanation for the empirical evidence, we would argue that there is scope for all three interpretations — hyperbolic discounting, similarity relations and sub-additive discounting — to play a role in different circumstances. Given the empirical evidence, the support for hyperbolic discounting is relatively strong.

Loewenstein and Prelec (1992) proposed that hyperbolic preferences could be modelled by a generalised hyperbolic discount function of the form:

$$D(t, \tau) = (1 + \varpi(t - \tau))^{-\xi/\varpi} \quad \text{for } \varpi, \xi > 0 \quad (1.33)$$

where the coefficient ϖ determines the extent of departure from exponential discounting. As $\varpi \rightarrow 0$ we obtain standard exponential discounting. When ϖ is large, $D(t)$ approximates a step function. Note that in the literature, ‘hyperbolic discounting’ has increasingly been employed to refer to *any* declining discount rate, not just discount functions that follow a hyperbola.

Variations on the hyperbolic theme have discount rates which are non-zero in the long run. For instance, Barro (1999) uses a discount function which is equivalent to $D(t, \tau) = e^{-[\underline{\delta}(t-\tau) + \phi(t, \tau)]}$, where $\phi'(t, \tau) = (\bar{\delta} - \underline{\delta})e^{-\chi(t-\tau)}$. This discount function is shown in Figure 1.1. The corresponding discount rate is given by $\underline{\delta} + (\bar{\delta} - \underline{\delta})e^{-\chi(t-\tau)}$. The discount rate starts at $\bar{\delta}$ when $t = \tau$ and falls exponentially at rate χ to $\underline{\delta}$ in the long run, as t approaches infinity.

In discrete time, the hyperbolic function can be approximated by a quasi-hyperbolic function, used originally by Phelps and Pollak (1968), later by Akerlof (1991) and popularised by Laibson (1997). It can be represented as a series of discount factors $\{1, \beta\zeta, \beta\zeta^2, \beta\zeta^3, \dots\}$, plotted in Figure 1.1³⁶. Like the specification in Barro (1999), the implicit long-run discount rate

³⁶For comparison, standard discounting in discrete time is represented by the discount factors $\{1, \zeta, \zeta^2, \zeta^3, \dots\}$

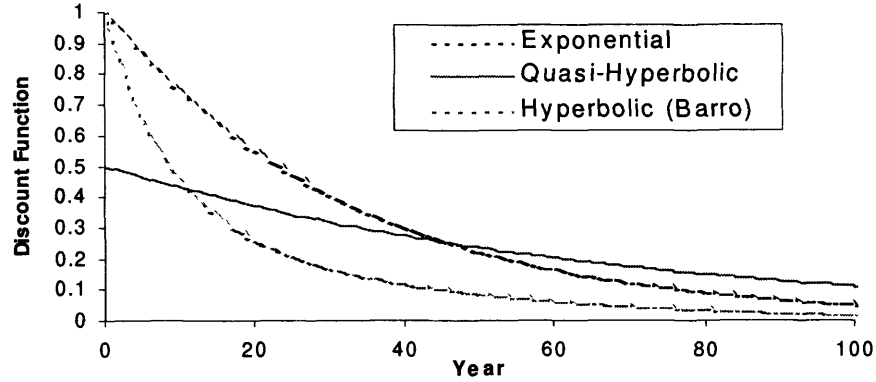


Figure 1.1: Hyperbolic discount functions.

is non-zero. Moreover, the quasi-hyperbolic function retains the qualitative properties of the hyperbolic function and is significantly more tractable.

1.6.2 Implications of hyperbolic discounting

Because hyperbolic and quasi-hyperbolic discounting imply a time-varying discount rate, they can result in time-inconsistent preferences³⁷. Consider a quasi-hyperbolic discounter with discount factors $\{1, \beta\zeta, \beta\zeta^2, \beta\zeta^3, \dots\}$. From the perspective of self t , the discount factor between $t+1$ and $t+2$ is ζ . However, from the perspective of self $t+1$ the discount factor between $t+1$ and $t+2$ is $\beta\zeta$. This time inconsistency implies that plans made today will not be carried out tomorrow unless a mechanism to commit the later self can be planned.

Because of this feature, Akerlof (1991) suggested that hyperbolic discounting might have useful applications to model procrastination, drug addiction, undersaving, and organisational failure, inter alia. In the last five years, more detailed hyperbolic models have emerged and have been applied to an enormously large range of economic phenomena. Laibson (1994, 1997), and Laibson et al. (1998) have considered the problem of undersaving in depth. Harris and Laibson (2001, 2003) extend this work to model buffer-stock saving. Retirement timing is considered by Diamond and Koszegi (1998). Drug addiction is examined by Gruber and Koszegi (2001), while O'Donoghue and Rabin (1999a,b) and Benabou and Tirole (2000) have examined procrastina-

where $\zeta \approx e^{-\delta}$, the continuous-time analogue.

³⁷A formal statement of this proposition, including specification of the features of the discount function that generate time inconsistency, is provided by Hepburn (2004).

tion. Barro (1999) shows that, under certain circumstances, optimal growth trajectories under hyperbolic discounting are observationally equivalent to those under exponential discounting. In the environmental sphere, Cropper and Laibson (1999) consider the effect of hyperbolic discounting in project evaluation and qualitatively consider the arguments for applying a lower discount rate to environmental projects.

1.7 Practical Implications for CBA

1.7.1 A brief summary so far

The preceding Sections have provided several rationales for DDRs. In a deterministic world DDRs can arise as a result of known changes in the growth rate, changes in consumption smoothing/risk aversion, increasing expenditures on the environment in the presence of environmental externalities, or increases in marginal WTP for the environment. Clearly each rationale has its strengths and weaknesses. Additional motivations emerge once uncertainty is considered. Uncertainty of the discount rate itself provides a simple and intuitive approach in a risk neutral environment. In the presence of uncertain growth Gollier shows that DDRs depend upon preferences for risk and prudence, and higher order moments of the utility function. Regardless of whether it is the discount rate or the growth rate that is uncertain, DDRs depend upon the nature of the underlying probability distribution. DDRs also emerge from the specification of a ‘sustainable’ welfare function à la Chichilnisky (1997) and Li and Löfgren (2000). Lastly, there is considerable empirical and experimental evidence to show that individuals are frequently hyperbolic discounters.

In sum, the practitioner is left with a confusing array of rationales for DDRs and little guidance as to the implications of employing them nor how to construct a workable schedule. In the following Sections we address these points directly.

1.7.2 Parameter identification

In answer to the first issue raised in this paper – whether DDRs can be justified - Sections 2-5 provided a variety of rationales for the use of declining discount rates. Once a rationale has been subscribed to, implementation requires the practitioner to identify a particular set of parameters, i.e. an answer to the second question raised: what trajectory a DDR should follow? The required parameters for determining the time invariant discount rate in the deterministic

case have been discussed extensively elsewhere (see, for example, Pearce and Ulph, 1999) and are well understood. Here we focus upon the application of the more recent contributions.

Horowitz (2002) reduces the discussion of the discount rate to a valuation problem: valuing future preferences. This requires analysis of the effects on WTP of changes in income and environmental quality. However, we noted that there are strong arguments for keeping ‘the’ discount rate separate from valuation of goods and services. Weitzman’s deterministic model (Weitzman 1994) requires information on the trend of the proportion of income spent on environmental goods (environmental protection), and the effectiveness of this expenditure in maintaining environmental standards in order to derive a DDR. These can be thought of as aggregate statistics in his model, and the theory is perhaps easily applied in this sense. However, the mechanism by which discount rates are affected, although intuitive, is quite particular.

In order to implement the approach suggested by Weitzman (1998), it is necessary to characterise the uncertainty of the interest rate. In general terms this amounts to defining a probability distribution for the future discount rate, and its behaviour over time. In this sense there are 2 ways in which we can interpret the example in Table 1.1. Firstly, it could represent the thought experiment of Weitzman (1998), in which we are currently uncertain about interest rates, and yet the interest rates will persist indefinitely ex post realisation. In this sense we have a probability distribution for the current uncertainty, which assumes that interest rates of 2 and 5% are equally likely, and we employ this distribution for all future periods. Uncertainty is therefore regarded as existing from day one, and all that is required is the current probability distribution of the discount rate.

In a further article, Weitzman (2001) takes precisely this approach. In order to establish the probability distribution for the socially optimal discount rate he undertakes a survey of over 2000 academic economists, and a so-called ‘blue ribbon’ selection of 50, as to their opinion on the constant rate of discount to use for CBA. The responses were distributed with a gamma distribution with mean 4%, and standard deviation 3%, providing an ad hoc working assumption to determine the schedule of DDRs. The assumption implicit in the use of the gamma distribution is that there is there is uncertainty in the present about the interest rate in the future and that when uncertainty is resolved the realised interest rate will persist forever.

Newell and Pizer (2003) take an alternative view. Rather than assuming uncertainty in the discount rate represents a current lack of consensus about *the* discount rate, they consider the interest rate as a stochastic process, that is there is uncertainty in the future about interest

rates. N&P characterise this uncertainty using time series econometric modelling of the autocorrelation process of interest rates. The estimated model is used to forecast future rates based upon their behaviour in the past. From these forecasts they derive numerical solutions for the CER. In doing so they are also able to provide a test of another assumption important to the Weitzman (1998) result, namely the presence of persistence of discount rates over time. They compare the discount rates modelled as a mean reversion process to a random walk model, and find support for the latter. The practical implications of implementing the declining discount rates that result are significant. When applied to global warming damages, the present value of damages from carbon emissions increases by 82%, compared with the same damages evaluated at the constant treasury rate of 4%. In monetary terms this translates into an increase in the benefits of carbon mitigation from \$5.7/ton of carbon, to \$10.4/ton of carbon. In the following Section we provide an application of this method to UK data, which indicates the importance of persistence.

In addition to determining the probability distribution, it is necessary to make some assumption concerning the point in time at which uncertainty concerning the discount rate begins. Weitzman (1998) suggests employing the declining discount rate at some period T , beyond which uncertainty is said to begin, but gives no particular guidance as to how to identify this. It seems reasonable to suggest that the limits of financial markets define a useful starting point for uncertainty. Government bonds generally have the longest maturity dates and reflect the market evaluation of future discount rates up to around 30 years in general. Hence $T = 30$ could be the point beyond which the certainty equivalent analysis should begin (e.g. as argued in OXERA 2002). Newell and Pizer (2003) implicitly assume that the uncertainty begins immediately, although, with high levels of persistence, the forecast remains relatively constant over the short-term.

The rationale for declining discount rates provided by Gollier (2002a, 2002b) is perhaps the most theoretically rigorous of all the contributions, given the apparent indeterminacy surrounding Weitzman (1998). But determination of the trajectory requires very specific information concerning the preferences of current generations at the very least, and, in the long-run, the preferences of future generations³⁸. These parameters include the aversion to consumption

³⁸With the infinitely lived representative agent approach there is effectively only one agent, and thus one generation. The reference to current and future generations is therefore an intuitive interpretation of the long-run.

fluctuations over time, the pure time preference rate, and the degree of relative risk aversion. With *i.i.d.* growth shocks with growth almost surely positive, restrictions on the 4th and 5th derivatives of the utility function become necessary. In addition, the nature of the certainty surrounding growth needs to be characterised in some way. Clearly, the informational requirements of the Gollier approach could be daunting.

Implementation of the Li and Löfgren and Chichilnisky approaches requires the identification of several other parameters, including specification of the utility discount rate for the ‘utilitarian’, and perhaps more importantly, the relative weight to be assigned between ‘conservationist’ and ‘utilitarian’ preferences. Although the selection of this weighting might appear to be relatively arbitrary, it makes the trade-off between present and future generations explicit, and could possibly be determined by an appropriate political process.

1.7.3 Time inconsistency

Dynamic inconsistency, or ‘time inconsistency’, arises when a plan determined to be optimal at a particular point in time is not optimal when considered at a later point in time. In this case, if the planner is unable to somehow commit future planners to the original plan, the plan will eventually be abandoned. It has been clear since Strotz (1956) that the myopic use of non-exponential discounting results in time-inconsistent plans. Indeed, as described in Section 1.6, hyperbolic discounting has had success in the behavioural economics literature precisely because its concomitant time inconsistent behaviour helps to explain phenomena such as procrastination and addiction. Generally, well-being is not maximised in such situations.

Faced with this potential for dynamic inconsistency, a government without a commitment mechanism can formulate policy in a ‘naïve’ or ‘sophisticated’ manner. Neither situation is satisfactory. The sophisticated government takes into account the fact that future governments will have an incentive to deviate from its optimal (committed) policy. The situation may be modelled as an intertemporal game played with its successors. In the Nash equilibrium, the government makes policy as the best response to successive government’s best responses. It therefore manages to retain credibility and, as Barro (1999) and Karp (2003) illustrate, time-consistency. However, the Nash equilibrium is not Pareto optimal. Interestingly, under certain conditions discussed in Barro (1999) this Nash equilibrium policy ends up being equivalent to a policy that would have been constructed using a conventional exponentially declining discount rate. In contrast, the ‘naïve’ government presses ahead regardless with dynamically inconsistent

policy, ignoring the fact that future governments will find its policies to be sub-optimal. This is also clearly sub optimal, as from the perspective of the current 'naïve' government, its optimal policy will not be adhered to.

Some writers do not see this to be a problem. For instance, Henderson and Bateman (1995) argue that the process of changing the discount rate as time moves on is legitimate. They assert that people see themselves living in relative, rather than absolute, time. Revising and re-evaluating plans as time moves on is not only consistent with behavioural studies, but with the value judgement that what ought to be done by way of discounting should reflect what people actually do. However, for others, ourselves included, it is not clear that empirical evidence of individual preferences is entirely relevant to the social discount rate. A Humean would contend that simply because people *do* discount the future hyperbolically does not mean that they *should*, nor does it imply that this is advisable practice for government. On the other hand, one might argue that if people's preferences count, and if people employ hyperbolic discounting, those preferences must be integrated into social policy formulation. The utilitarian leaps effortlessly from 'is' to 'ought' statements because of the assumption that behaviour reflects preferences.

Nevertheless, this assumption has been questioned not only by philosophers but also by economists such as Feldstein (1964). Indeed, more recently, a literature on 'optimal paternalism' is developing which suggests, amongst other things, that governments may be justified in intervening not only to correct externalities, but also to correct 'internalities'; behaviour that is damaging to the actor. Recent work on sin taxes by O'Donoghue and Rabin (2003) provides an example of this type of approach. Whether or not one supports a paternalistic role for government, however, the wisdom of adopting a discount function that explains procrastination and addiction for social policy is questionable. Our overall conclusion is that although the evidence that individuals employ hyperbolic discounting is strong, the argument that governments should do likewise is weak. We conclude that this Section undoubtedly puts forward the least persuasive of the arguments for declining social discount rates.

Heal (1998) takes a different tack in arguing that time consistency is not significant. He notes that at an individual level, individuals at different stages of life might appropriately be thought of as different people, so that requiring time consistency is somewhat stringent. We know from the theory of preference aggregation that societies generally satisfy weaker rationality conditions than their composite individuals, so from a social choice perspective time consistency

is a ‘most unnatural requirement’. While this is correct, the consequences of time inconsistency at a social level, just as the individual level, can be particularly severe. Hepburn (2003), for instance, shows that a naïve government employing a hyperbolic (declining) discount rate in the management of a renewable resource can unwittingly manage the resource into extinction.

Newell and Pizer (2003) argue that they are able to ‘circumvent’ the time inconsistency problem. In their model, the decline in future discount rates follows from uncertainty about future events rather than an underlying preference for a deterministically declining discount rate. But it is not clear that this circumvents the problem at all. Irrespective of the theoretical or empirical basis for the use of declining discount rates, if they are used naïvely a time inconsistent policy will result. As Hepburn (2003) notes, building awareness of the problem, thereby encouraging the use of declining rates in a sophisticated or committed manner, is surely better than assuming it away.

There is no easy resolution of the time-inconsistency problem. Incongruence, or dynamic inconsistency, results in consumption and savings plans that are sub-optimal for all generations. Heal (1998) proves that almost all types of declining discount rates are time inconsistent, so the extent of the problem is certainly significant. As a practical matter, however, the dynamic inconsistency inherent in declining discount rates may not be any more troubling than policy inconsistencies and changes that are prompted by external shocks or political shifts. More work is needed in this area.

1.8 Implications of Declining Discount Rates: Some UK case studies

In this Section we investigate the implications of DDRs for policy. We employ some of the methodologies described above to two issues: climate change and nuclear power. This involves an application of the Weitzman/Newell and Pizer (2003) approach to UK interest rate data.

1.8.1 Uncertainty of UK interest rates in the future

In this Section we describe a declining discount rate schedule derived from the application of the estimation procedure used by Newell and Pizer (2003) (N&P) to UK interest rate data. In short, interest rates are forecasted over a period of 400 years using the results of an estimated reduced form random walk model. The schedule of certainty equivalent discount rates is derived

from the simulation of up to 100,000 interest rate forecasts and use of Weitzman's definition of the certainty equivalent discount rate (CER). The details of the econometric models used are shown in Chapter 3³⁹.

One interesting difference in the application of N&P's method to UK data is that, contrary to the US case, we fail to establish the existence of persistence. Hence the mean reverting model is more appropriate than the random walk model in the UK case. The presence of persistence is of considerable importance where uncertainty in the discount rate itself drives DDRs.

1.8.2 Social cost of carbon

The social cost of carbon is an estimate of the present monetary value of damage done by anthropogenic carbon-dioxide emissions. The UK has an 'official' value of this shadow price (Clarkson and Deyes 2002) at £70 per tC, although the validity of the number is disputed (Pearce 2003) and the official value is under review at the time of writing. Self-evidently, higher values of the social cost of carbon imply that investment in climate change mitigation is more attractive. The discounting framework employed has a significant impact upon such estimates. It is obvious, for instance, that a lower (constant) discount rate will increase the present value of the marginal damage from emissions. For example, the marginal damage values from the Fund 1.6 model (Tol 1999) increase from \$20/tC to \$42/tC to \$109/tC, as the discount rate declines from rates of 5% to 3% to 1% respectively.

In order to illustrate the difference between the various discounting frameworks on the social cost of carbon, we start with an approximate profile of the economic damage done by one tonne of carbon emissions in 2000, shown in Figure 1.2. This is the profile of damages generated by the DICE model of Nordhaus and Boyer (2000). Applying the various discounting regimes to this damage profile over the next 400 years results in estimates of the social cost of carbon presented in Figure 1.3. For the 200-year period, the estimates vary from approximately £2.50/tC at a 6% flat discount rate, to about £20.50/tC under a discounting regime based on the Li and Löfgren approach.

Increasing the time horizon from 200 to 400 years makes no difference when constant discount rates are employed, because the discount factor approaches zero well before the 200 year mark. In contrast, marginal damage estimates under declining discount rate regimes are

³⁹The simulation method is explained in more detail in Chapter 3 in which the issue of model selection is taken up.

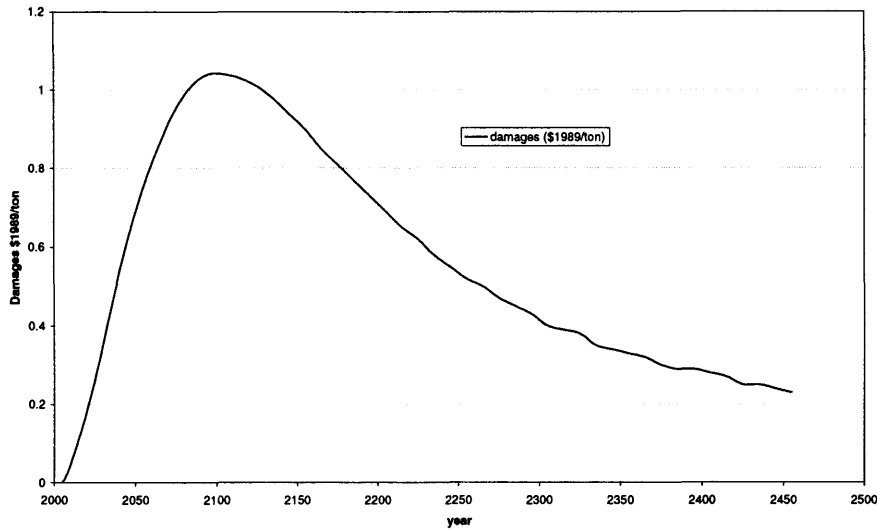


Figure 1.2: The profile of carbon damages from the DICE model.

noticeably larger when the time horizon is extended to 400 years.

Furthermore, the application of N&P's methodology to UK data increases the 400 year estimates of marginal damage costs by a mere 4.3% compared to the constant discounting regime. This contrasts with N&P's finding of an 84% increase. This reflects the lower level of persistence found in the UK case compared to the US, resulting in the mean reverting model being more appropriate than the random walk model of N&P. This highlights another practical issue concerning selection of the appropriate model for the interest rate⁴⁰.

This illustration suggests that estimates of the social cost of carbon are likely to at least double if declining discount rates are employed. This would have formidable implications for policy in several areas. For example, a higher social cost of carbon would make it more likely that commitments to Kyoto targets would pass a cost-benefit test (Pearce, 2003).

1.8.3 Nuclear power

New nuclear build in the UK is still being considered as an option to ensure security of energy supply and meeting long run climate change targets. In 1998, the House of Commons Trade and Industry Committee recommended that: 'A formal presumption be made now, for purposes of long-term planning, that new nuclear plant may be required in the course of the next two

⁴⁰This is the subject of Chapter 3.

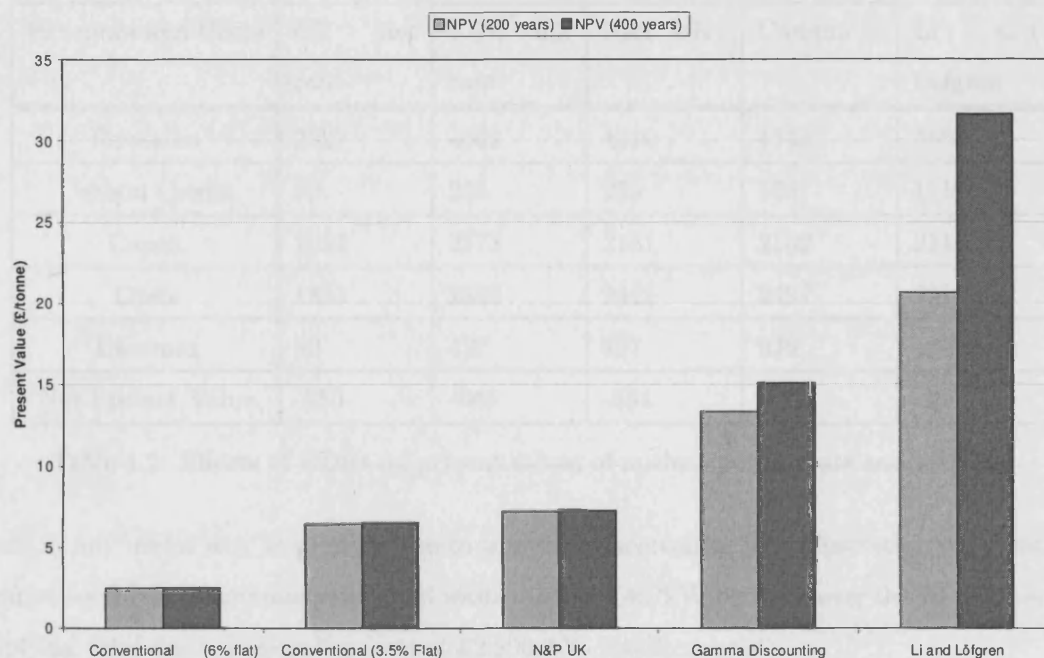


Figure 1.3: The discounted values of the damage from a ton of carbon

decades.' This recommendation has been supported by a joint working group of the Royal Society, and the Royal Academy of Engineering. More recently, the Performance and Innovation Unit (Performance and Innovation Unit, 2002a) recommended that the nuclear option should be kept open.

These recommendations are based upon conventional assessments of the economics of new nuclear build, which are 'relatively insensitive to back end costs.' (Performance and Innovation Unit, 2002b). In other words, the present-value of decommissioning costs is insignificant using conventional discounting. However, the present-value costs of decommissioning approximately double if declining discount rates are employed. From PIU (2002b) we assume a construction cost of £2,250/kW in 2000, and a load factor of 0.85. Employing submissions from the NUCG to the 1995 White Paper on The Prospects for Nuclear Power in the UK, we assume variable operating and maintenance cost of 0.6p/kWh, and fuel cost of 0.4p/kWh, in 1993 money. We assume fixed operating costs of 1.5% of construction cost. Construction occurs over six years, the reactor lifetime of 40 years, and decommissioning and waste management occurs over the following 70 years. PIU (2002b) state that 'it is impossible to estimate waste management

Revenues and Costs	6% flat rate	3.5% flat rate	N&P UK	Gamma	Li and Lofgren
Revenues	2527	4062	4210	4343	3853
Carbon Credit	90	228	255	528	1110
Capex	2054	2173	2181	2152	2116
Opex	1453	2336	2421	2497	2216
Decomm	90	427	497	939	1192
Net Present Value	-980	-646	-634	-717	-560

Table 1.2: Effects of DDRs on present values of nuclear power costs and revenues

costs in any useful way at present' due to immense uncertainty. For illustration purposes, we assume combined decommissioning and waste costs of £40/kW per year over the 70 year period, implying total decommissioning costs of £2,800/kW (undiscounted).

As table 1.2 illustrates, our calculations suggest that decommissioning costs would increase from approximately £90/kW, with a flat 6% discount rate, to £1,190/kW applying the approach of Li and Löfgren. At this level, decommissioning and waste costs are a major determinant of the economic viability of nuclear power and can no longer be relegated to the realm of politics.

But there are two further countervailing effects. Firstly, a declining discount rate increases the present-value of the generation revenue earned over the 40-year lifetime of the reactor. In other words, declining discount rates reduce the weight on the initial front-end costs and increase the relative weighting on revenue earned in the future. Secondly, if an emissions tax based upon the social cost of carbon were imposed upon conventional generators, declining discount rates would improve the relative economics of nuclear generation by raising the social cost of carbon. The size of these effects, based upon the assumptions employed above, is presented in Table 1.2 below.

1.9 Conclusions

The realisation that actions taken today can have long term consequences presents a challenge to decision makers in assessing the desirability of policies and projects. The use of the classical net present value (NPV) rule to assess the economic efficiency of policies with costs and benefits that accrue in the long term is felt by many to be particularly problematic. The welfare of

future generations barely influences the outcome of such a rule when constant socially efficient discount rates are used for all time. The deleterious effects of exponential discounting ensure that projects that benefit generations in the far distant future at the cost of those in the present are less likely to be seen as efficient, even if the benefits are substantial in future value terms. In this respect it appears that the present wields a dictatorship over the future. The idea of using Declining Social Discount Rates (DDRs) has emerged largely in response to these awkward implications and recently DDRs have even been entertained at an official level in the UK (HM Treasury 2003).

This paper critically reviews the theoretical justifications for DDRs and discusses the practical implications of determining a schedule of DDRs for use in CBA. We take the familiar Ramsey growth model as our starting point and discuss the recent contributions to the literature on DDRs for social cost benefit analysis (CBA). Where possible we have related these contributions to this model and the benchmark definition of the socially efficient discount rate when consumption is the numeraire, reflected by the familiar Ramsey rule. The Utilitarian principles that underpin the Ramsey model and conventional CBA also underpin many of the theoretical arguments for DDRs accordingly hinge upon the behaviour of optimising individuals. That said, the rationales presented here are manifold and various, some are deterministic in nature while others deal with uncertainty, some consider efficient discount rates while others are concerned more with intergenerational equity and sustainability.

Dasgupta et al. (1999) and Dasgupta (2001) remind us to be aware of the assumptions underlying the Ramsey rule and the use of a constant discount rate. The implied partial equilibrium commonly assumed in CBA certainly does not hold in the calamitous scenarios often used to exemplify the effects of constant discounting. In such scenarios the efficient discount rate will be declining with income, and more weight will automatically be placed on the future.

Gollier (2002a, 2002b, 2004b) and Weitzman (1998) are also concerned with determining the socially efficient discount rate, but under uncertainty with regard to growth and the discount rate respectively. They provide the conditions under which the social discount rate is declining. Naturally, the presence of uncertainty introduces a number of complications. Firstly, as the contributions make clear (e.g. Weitzman 1998, Newell and Pizer 2003, Gollier 2004b), the nature of uncertainty; the probability distribution and its behaviour over time, are important determinants of the schedule of discount rates. Existing attempts to determine the nature of

uncertainty have been more exploratory than rigorous (e.g. Weitzman 2001). Of particular importance is the presence of persistence in the random variable of interest and there exist several empirical tests for this in the literature (Newell and Pizer 2003).

A second complication introduced by the presence of uncertainty is the nature of individual preferences for risk. Weitzman's analysis (Weitzman 1998) circumvents this issue to some extent by assuming risk neutrality. However, according to Gollier (2004a) this only raises another question: who should bear the risk of investments, the present or the future? In the absence of risk preferences any decision is arbitrary but the outcome is starkly different in each case: if we think that future generations should bear the risk associated with discount rates, the socially efficient discount rate is *increasing* over time rather than decreasing! Under risk neutrality however, economics can contribute little to this choice.

Gollier shows that when growth is uncertain preferences for risk are a fundamental determinant of the schedule of discount rates (Gollier 2002a, 2002b, 2004b). In particular, for the socially efficient discount rate to be declining requires such preferences to take very particular form: where growth risk is *i.i.d.* DDRs depend upon the sign of the 4th or 5th derivatives of the utility function. Although the preferences become less restrictive once more realistic assumptions are introduced with respect to growth risks, whether DDRs emerge remains a relatively complicated empirical question.

The question of how individuals actually discount time has been the focus of much economic and psychological research. It is commonly found that individuals employ hyperbolic discount rates. Although some commentators have suggested that such preferences should be reflected in social choice mechanisms such as CBA (Henderson and Bateman 1995), very much reflecting the ethical underpinnings of this methodology, we express reservations about adopting a rationale for DDRs which has had success in explaining apparently irrational behaviour such as drug addiction and procrastination. In short, like Hume, we disagree that 'is' statements should lead directly to 'ought' statements in this case.

Further justification for DDRs is provided by Chichilnisky (1997) and Li and Löfgren (2000) who move away from the strict Utilitarian Ramsey framework and address the issue of inter-generational equity and sustainability head-on. They provide an axiomatic justification for the use of declining *utility* discount rates, as opposed to the consumption discount rates that are the focus in the previous contributions. In these cases DDRs ensure that a non-dictatorship axiom is satisfied: the present does not act as a dictator over the future nor vice versa. In the

Li Löfgren model, this decline is determined by the choice of weights applied to the Utilitarian and the Conservationist components of the objective function.

The approaches reviewed here are predominantly theoretical contributions to an inherently practical issue. Ultimately, the practitioner is faced with a potentially confusing array of rationales and a sense that almost any discount rate can be applied. Moreover, it is important that the practitioner is aware that the implications of employing declining discount rates are of considerable moment. Firstly, as our case studies show, there is the potential to reverse the recommendations of social cost benefit analysis in the long-term policy arena. This is especially important given the nature of this policy arena and the considerable changes that might be required in order to prevent the impact of global warming. Secondly, declining discount rates introduce time- inconsistency to the decision making process. This is likely to be problematic for the practitioner, and in some cases can lead to problems of resource exhaustion (Hepburn 2003). The stakes are potentially very high in this arena and, to the extent that economic analysis is used on both sides of the argument in international policy-making, the analysis must be robust and well conceived.

That social discount rates should be declining is still not clear, despite the sometimes compelling contributions described above. In many cases only the conditions under which DDRs are said to exist have been defined. Whether or not these conditions prevail is another question altogether. Indeed, the use of DDRs may put us in danger of placing more weight upon potentially far richer individuals in the far distant future that we place on present, or even near future generations. What is more widely agreed is the limited extent to which discount rates can be manipulated to simultaneously reflect the numerous underlying issues that have motivated their investigation, namely inter-generational equity, sustainability and efficiency. Practitioners would be wise to note this as well as the potentially fundamental limitations of CBA in dealing with long -term investments (Lind 1995).

1.10 Remaining Issues and Puzzles

Section 1.4 presented the most recent contributions to the literature on declining interest rates all of which were based upon uncertainty of some description. This author believes that these contributions not only provide the most compelling reasons for using DDRs in project appraisal but also present fertile ground for future research. Indeed, a number of complications and gaps

in the analysis of declining discount rates were highlighted in the foregoing, some practical and others theoretical. Of these, the most interesting were those concerned with the arguments for DDRs under uncertainty. In an uncertain world the gaps in the literature and the associated complications can be placed into 2 broad groups:

1. preferences for risk and other moments and;
2. the characterisation of uncertainty.

In the following 2 chapters we address two outstanding issues, one from each of the broad groups above.

In Chapter 2 we focus on an issue from group (i). We address the puzzle highlighted by Gollier (2004a) described in Section 1.4. To recap, Gollier noted a problem associated with Weitzman's certainty equivalent rate (Weitzman 1998), namely that the schedule of efficient discount rates differs depending upon whether we choose to maximise the Expected Net Present Value (ENPV) or Expected Net Future Value (ENFV) of investments. Under certainty there is no difference between these two criteria, however once uncertainty in the discount rate is introduced the schedule of efficient discount rates is declining when maximising ENPV and increasing when maximising ENFV. In resolving this puzzle Gollier argues that the practitioner must make some arbitrary decision concerning the inter-temporal allocation of risk. Chapter 2 resolves this puzzle and describes the implications for CBA that emerge from this resolution.

In Chapter 3 we refine existing methodologies for characterising the uncertainty surrounding the discount rate. In this way we provide practical recommendations for determining the schedule of discount rates using Weitzman's definition of the certainty equivalent rate. There has been two attempts in the environmental literature to characterise the uncertainty that drives DDRs, each of which has interpreted uncertainty in a different way and both of which have been exploratory rather than rigorous. Weitzman (2001) established the distribution of current opinions with regard to the discount rate to be used for CBA. In this way the theory of Weitzman (1998) could be operationalized. Newell and Pizer (2003) took an alternative view of the nature of uncertainty in estimating the certainty equivalent discount rate, characterising the discount rate as a random variable and estimating the schedule via time-series econometrics. As will become clear, Chapter 3 shows that Newell and Pizer (2003) do not provide a complete answer to the question of how to determine the schedule of certainty equivalent discount rates

when the discount rate is characterised as a stochastic variable. A more precise methodology is proposed and empirically tested.

1.11 References

Akerlof, G. A. 1991. Procrastination and Obedience. *American Economic Review*, 81(2), 1.

Arrow K.J., 1966. Discounting and Public Investment Criteria. in Kneese A.V. and Smith S.C. (eds) *Water Research*, Baltimore.

Arrow, K., Cline, W., Maler, K-G., Munasinghe, M., Squitieri, R. and Stiglitz, J. 1995. Intertemporal equity, discounting and economic efficiency, in Bruce J.P., Lee, H., and Haites, E. (eds), p128-144. Cambridge University Press, Cambridge.

Atkinson, G., Dubourg, R., Hamilton, K., Munasinghe, M., Pearce, D.W and Young, C. 1997. *Measuring Sustainable Development: Macroeconomics and the Environment*, Cheltenham: Edward Elgar.

Azfar, O. 1999. Rationalizing hyperbolic discounting. *Journal of Economic Behavior & Organization*, vol. 38(2), p245-252.

Barrett, S., Dasgupta, P., and Mäler, K.-G., 1999. "Intergenerational Equity, Social Discount Rates, and Global Warming", in P.R. Portney and J.P. Weyant, eds., *Discounting and Intergenerational Equity* (Washington, D.C.: Resources for the Future), 1999, p 51-78.

Barro, R. J., 1999. Ramsey Meets Laibson in the Neoclassical Growth Model. *Quarterly Journal of Economics*, 114(4), p1125-1152.

Barro, R.J. and King, R.G. 1984. Time Separable Preferences and Intertemporal-substitution models of business cycles. *Quarterly Journal of Economics*, 99(4), p817-839.

Baumol, W.J. 1968. On the social rate of discount. *American Economic Review*, 57, p788-802.

Benabou, R. and J. Tirole 2000. Willpower and personal rules, mimeo.

Benhabib, J., A. Bisin, and A. Schotter 2004. Hyperbolic discounting and self-control: An experimental analysis. mimeo.

Bradford D.F., 1999. On the Uses of Benefit-Cost Reasoning in Choosing Policy toward Global Climate Change. Chapter 5 in Portney, P and Weyant, J. (eds). 1999. *Discounting and Intergenerational Equity*, Washington DC: Resources for the Future.

Brock, W.A. 1977. A polluted golden age. In Smith, V. (ed), *Economics of natural and*

environmental resources, New York, Gordon and Breach.

Broome, J. 1992. *Counting the Cost of Global Warming*. Cambridge: White Horse Press.

Chichilnisky, G., 1996. An axiomatic approach to sustainable development. *Social Choice and Welfare*, 13, p231–257.

Chichilnisky, G., 1997. What is sustainable development? *Land Economics*, 73, p467–491.

Chichilnisky, G., and Heal, G., 1997. Social choice with infinite populations: construction of a rule and impossibility results. *Social Choice and Welfare*, 14(2): p303-319.

Clarkson, R and Deyes, K., 2002. Estimating the Social Cost of Carbon Emission, Government Economic Service Working Paper 140, London, HM Treasury, February. Available at [www.hm-treasury.gov.uk/documents/taxation work and welfare/taxation and the environment](http://www.hm-treasury.gov.uk/documents/taxation%20work%20and%20welfare/taxation%20and%20the%20environment).

Cowell, F A and Gardiner, K. 1999. Welfare Weights, STICERD, London School of Economics, Research Paper 20, August.

Cropper, M. and D. Laibson 1999. The Implications of Hyperbolic Discounting for Project Evaluation. In *Discounting and Intergenerational Equity, Resources for the Future*, p163-172.

Cropper, M. L., S. K. Ayded, and P. R. Portney 1994. Preferences for Life Saving Programs: How the Public Discounts Time and Age, *Journal of Risk and Uncertainty*, 8, p243-265.

Dasgupta, P. 2001. Discounting: How and Why?. mimeo. Beijer Institute.

Dasgupta, P. and Maskin, E. 2002. Uncertainty, waiting costs and hyperbolic discounting. Beijer Institute discussion paper no 158.

Diamond, P. and B. Koszegi 1998: Hyperbolic discounting and retirement, mimeo.

Dickey D.A. and Fuller W.A. 1979. Distribution of the Estimators for Autoregressive Time Series with a Unit Root. *Journal of the American Statistical Association* 74, (1979), 427-431.

Dybvig, P. and Ingersoll, J. and Ross, S. 1996. Long Forward and Zero-Coupon Rates Can Never Fall. 69:1 *Journal of Business* 1-25.

Elliott G., Rothenberg, T.J. and Stock J H. 1996. Efficient Tests for an Autoregressive Unit Root. *Econometrica* 64, 813-836.

Feldstein, M. S. 1964. The social time preference discount rate in cost benefit analysis. *Economic Journal*, 74(294), p360-379.

Fisher and Krutilla 1975. Resource Conservation, Environmental Preservation, and the Rate of Discount. *Quarterly Journal of Economics*, 89(3) p358-70.

Frederick, S., Loewenstein, G. and O'Donoghue, T. 2002, Time discounting and time preference: a critical review, *Journal of Economic Literature*, XL, p351–401.

- Gollier, C., 2001. *The Economics of Risk and Time*. Cambridge, MA: MIT Press.
- Gollier, C., 2002a. Time Horizon and the Discount Rate. *Journal of Economic Theory*, 107(2): p463-73.
- Gollier, C., 2002b. Discounting an uncertain future, *Journal of Public Economics*, 85, 149-166.
- Gollier, C., 2004a. Maximizing the Expected Net Future Value as an Alternative Strategy to Gamma Discounting. *Finance Research Letters*, vol. 1, n. 2, June 2004, p. 85-89.
- Gollier, C., 2004b. The Consumption based determinants of the discount rate. LERNA working paper # 04.20.157.
- Gravelle H and Smith D 2000. Discounting for Health Effects in Cost Benefit and Cost Effectiveness Analysis. Centre for Health Economics Technical Paper Series 20. University of York.
- Gray F.S. 1996. Modeling the Conditional Distribution of Interest Rates as a Regime-Switching process. *Journal of Financial Economics* 42, 27-62.
- Groom, B., Koundouri, P., Panopoulou, K., and Pantelides, T. 2004. Model Selection in discounting the distant future. Department of Economics, University College London Discussion paper 04/02.
- Gruber, J. and B. Koszegi 2001. Is Addiction Rational? Theory and Evidence. *Quarterly Journal of Economics*, 116(4), p1261-1305.
- Harris, C. and D. Laibson 2001. Dynamic choices of hyperbolic consumers. *Econometrica*, 69(4), p935-957.
- Harris, C. and D. Laibson 2003. Hyperbolic Discounting and Consumption. In *Advances in Economics and Econometrics: Volume 1*, Cambridge: Cambridge University Press, p258-297.
- Harvey. A.C. 2003. Long memory in stochastic volatility. mimeo, London School of Economics.
- Haveman, R.H., 1969. The opportunity cost of displaced private spending and the social discount rate. *Water Resources Research* 5(5), p252-277.
- Heal, G., 1998. *Valuing the Future: Economic Theory and Sustainability*, New York: Columbia University Press.
- Henderson, N and Bateman, I., 1995. Empirical and public choice evidence for hyperbolic social discount rates and the implications for intergenerational discounting, *Environmental and Resource Economics*, 5, 413-423.

Hepburn, C. 2004. Concerning the future: declining discount rates and intergenerational equity. Oxford University DPhil Thesis.

Hepburn, C., 2003. Hyperbolic discounting and resource collapse, Oxford University Department of Economics, Working Paper 159.

HM Treasury, 2003. The Green Book: Appraisal and Evaluation in Central Government: London: HM Treasury.

Horowitz, J., 2002. Preferences in the Future. *Environmental and Resource Economics* 21, 241-59.

Johannesson, M and Johannsson, P-O. 1996. To be or not to be. That is the question: an empirical study of the WTP for an increased life expectancy at an advanced age. *Journal of Risk and Uncertainty*. 13, 2. p163-174.

Kimball, M.S., 1990. Precautionary Saving in the Small and in the Large', *Econometrica*, 58, 53-73.

Kirby, K. N. 1997. Bidding on the Future: Evidence Against Normative Discounting of Delayed Rewards. *Journal of Experimental Psychology*, 126, p54-70.

Koopmans, T.C. 1965. On the concept of optimal economic growth, *Pontificae Academiae Scientiarum Scripta Varia*, 28, 225-300.

Koopmans. T.C. 1960. Stationary ordinal utility and impatience. *Econometrica* 28(2).

Krutilla, J and Fisher, A.C. 1975. *The Economics of Natural Environments*. Baltimore: Johns Hopkins University Press.

Kwiatkowski, D. , Phillips, P.C.B., Schmidt, P and Shin Y. 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? *Journal of Econometrics* 54, 159-178.

Kydland, F., and E.P. Prescott, 1977. Rules rather than discretion: the inconsistency of optimal plan, *Journal of Political Economy*, 85(3), 473-492.

Laibson, D. 1997. Golden Eggs and Hyperbolic Discounting. *Quarterly Journal of Economics*, 112, p443-477.

Laibson, D. I. 1994: Self-control and savings, Cambridge, MA: MIT Ph.D Thesis.

Laibson, D. I., A. Repetto, and J. Tobacman 1998. Self-Control and Saving for Retirement. *Brookings Papers on Economic Activity*, 1, p91-196.

Li, C. Z., and Lofgren, K. G., 2000. Renewable Resources and Economic Sustainability: A Dynamic Analysis with Heterogeneous Time Preferences' *Journal of Environmental Economics*

and Management, 40, 236–250.

Lind, R., 1982. A Primer on the Major Issues Relating to the Discount Rate for Evaluating National Energy Options', in Discounting for Time and Risk in Energy Policy, edited by R. Lind. Washington, Resources for the Future, p21-114.

Loewenstein, G and Prelec, D., 1992. Anomalies in intertemporal choice: evidence and an interpretation, Quarterly Journal of Economics, 107, p573-597.

Lucas, R.E. 1978. Asset Prices in an Exchange Economy. Econometrica 46, p1429-1445.

Maddison, A. 2001. The World Economy: A Millennial Perspective. Paris: Organisation for Economic Cooperation and Development.

Manne, A.S., 1995. The rate of time preference: implications for the greenhouse debate. Energy Policy 23(4/5) p391-394.

Mulligan, C. B. 1996. A Logical Economist's Argument Against Hyperbolic Discounting. University of Chicago, mimeo.

Newell, R and Pizer, W., 2001. Discounting the Benefits of Climate Change Mitigation: How Much do Uncertain Rates Increase Valuations? Pew Center on Global Climate Change, Economics - Technical Series, Arlington, VA. Available at www.pewclimate.org.

Newell, R. and Pizer, W. 2003. 'Discounting the benefits of climate change mitigation: how much do uncertain rates increase valuations?' Journal of Environmental Economics and Management, Vol. 46(1), p 52-71.

Ng, S. and P. Perron, 2001. Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power. Econometrica 69(6), 1519-1554.

Nordhaus, W.D. and Boyer, J., 2000. Warming the world: Economic Models of Global Warming, MIT Press, Cambridge, MA

O'Donoghue, T. and M. Rabin 1999a: Doing It Now or Later. American Economic Review, 89(1), p103-124.

O'Donoghue, T. and M. Rabin 1999b. Incentives for procrastinators. Quarterly Journal of Economics, 114(3), p769-816.

O'Donoghue, T. and M. Rabin 2003. Studying optimal paternalism, illustrated by a model of sin taxes. American Economic Review, 93(2), p186-191.

Olson, M and Bailey, M 1981. Positive time preference. Journal of Political Economy, 89(1), pp1-25.

OXERA, 2002. A Social Time Preference Rate for Use in Long-term Discounting. London:

Office of the Deputy Prime Minister, Department for Environment, Food and Rural Affairs, and Department for Transport.

Pearce, D, Groom, B., Hepburn, C and Koundouri, P. Valuing the Future: Recent Advances in Social Discounting. *World Economics*, 4(2) (2003), 121-141.

Pearce, D.W. and Ulph. D., 1999. A social discount rate for the United Kingdom, in Pearce, D.W., *Environmental Economics: Essays in Ecological Economics and Sustainable Development*. Cheltenham: Edward Elgar, p268-285.

Pearce, D.W., 2003. 'The social cost of carbon and its policy implications'. *Oxford Review of Economic Policy*, 19(3), pp.362-384.

Phelps, E. S. and R. A. Pollak 1968. On Second-Best National Saving and Game- Equilibrium Growth. *Review of Economic Studies*, 35(2), p185-199.

Phillips P.C.B. and Perron P 1988. Testing for a Unit Root in Time Series Regression. *Biometrika* 75, 335-346.

Pigou, A. 1932. *The Economics of Welfare*. 4th edition, Macmillan, London.

PIU Performance and Innovation Unit 2002. *The Energy Review* -February.

Portney, P and Weyant, J. (eds). 1999. *Discounting and Intergenerational Equity*, Washington DC: Resources for the Future

Pratt, J., 1964. Risk Aversion in the small and the large, *Econometrica*, 32, 122-136.

Rabl, A., 1996, Discounting of long term costs: What would future generations prefer us to do? *Ecological Economics*, 17, 137-145.

Ramsey, F.P., 1928. A mathematical theory of saving. *Economic Journal*, 38, 543-59.

Read, D. 2001. Is time-discounting hyperbolic or subadditive?. *Journal of Risk and Uncertainty*, 23(1), p5-32.

Rubinstein, A. 2003. Is it 'economics and psychology'? The case of hyperbolic discounting. *International Economic Review*, 44(4), p1207-1216.

Samuelson, P.A., 1965. Principles of Efficiency: Discussion. *American Journal of Economics*, proceedings, 54, p93-96.

Schwarz, G. 1978. Estimating the Dimension of a Model. *Annals of Statistics* 6, 461-464.

Stephane, G., Muller-Furstenburger, G. and Predivoli, P., 1997. Overlapping generations or infinitely lived agents. *Environmental and Resource Economics*, 10, p27-40.

Strotz, R. 1956. Myopia and inconsistency in dynamic utility maximisation, *Review of Economic Studies*, 23, 165-180

Thaler, R. H. 1981. Some Empirical Evidence on Dynamic Inconsistency. *Economic Letters*, 8, p201-207.

Tol, R.S.J., 1999. The marginal costs of climate change: towards more comprehensive calculations. *Energy Journal*, 20 (1), 61–81.

Tol, R.S.J., 2003. On dual-rate discounting. *Economic Modelling* 21, p95-98.

Tóth F.L., 2000. Intergenerational Equity and Discounting. *Integrated Assessment*, 1, p127-136.

Traeger C.P., 2004. Marginal Utility Propagation, Prices and the Rate of Discount: should environmental goods be discounted hyperbolically?. Paper presented at the annual European Association of Environment and Resource Economists conference, Budapest June 2004.

Weitzman, M. 1994. On the ‘environmental’ discount rate. *Journal of Environmental Economics and Management*, 26(1), p200-9

Weitzman, M., 1998. Why the far distant future should be discounted at its lowest possible rate, *Journal of Environmental Economics and Management*, 36, 201–208.

Weitzman, M., 1999. ‘Just keep on discounting, but...’. In P.Portney and J.Weyant (eds), *Discounting and Intergenerational Equity*, Washington DC, Resources for the Future, 23-30.

Weitzman, M., 2001. Gamma Discounting, *American Economic Review*, 91, 1, March, 261–271.

Weitzman, M.L., 2004. Statistical discounting of an uncertain distant future, mimeo, Harvard University.

1.12 Appendices

1.12.1 Appendix 1. The proof that $\lim_{t \rightarrow \infty} r_a^{CER} = r_{\min}$:

A rough sketch of the proof is as follows: r_a^{CER} can be thought of as the certainty equivalent of a random pay-off, \tilde{r} , for an agent with a constant degree of absolute risk aversion t . In particular preferences are reflected by $E[u(r)] = E[-\exp(-\tilde{r}t)] = -\exp(-r_a^{CER}t)$. As risk aversion increases, i.e. t increases, it is well known that the certainty equivalent will decrease (Pratt 1964). Furthermore, as $t \rightarrow \infty$, r_a^{CER} will tend to the lower bound of \tilde{r} : r_{\min} .

1.12.2 Appendix 2. Explicit example of Weitzman's Certainty Equivalent Discount Rate:

Suppose that there are two potential realisations of the discount rate (r_1, r_2) with associated probabilities (p_1, p_2) . Using the definitions (2.1) and (1.17) we obtain the certainty equivalent discount factor and rate at time t :

$$A(t) = p_1 \exp(-r_1 t) + p_2 \exp(-r_2 t) = p_1 a_1(t) + p_2 a_2(t) = \sum p_j a_j(t)$$

$$r_m^{CER} = -\frac{\dot{A}(t)}{A(t)} = \frac{r_1 p_1 a_1(t) + r_2 p_2 a_2(t)}{p_1 a_1(t) + p_2 a_2(t)} = w_1(t) r_1 + w_2(t) r_2 = \sum w_j(t) r_j$$

where $w_1(t) = p_1 a_1 / (p_1 a_1 + p_2 a_2)$ and $w_2(t) = p_2 a_2 / (p_1 a_1 + p_2 a_2)$ and $\sum w_j(t) = 1$. This formula is used for r_m^{CER} in Table 1.1. The formula for r_a^{CER} is:

$$r_a^{CER} = -\frac{1}{t} \ln [p_1 \exp(-r_1 t) + p_2 \exp(-r_2 t)]$$

Using (1.19) and the fact that:

$$\dot{w}_j(t) = \frac{p_j a_j(t)}{\sum p_j a_j(t)} \cdot \frac{\sum r_i p_i a_i(t)}{\sum p_i a_i(t)} - \frac{r_j p_j a_j(t)}{\sum p_j a_j(t)} = w_j(t) (r_m^{CER} - r_j)$$

the derivative of r_m^{CER} with respect to time then becomes:

$$\frac{d}{dt} r_m^{CER} = -[w_1(r_m^{CER} - r_1) r_1 + w_2(r_m^{CER} - r_2) r_2] = -\sum w_j(t) (r_m^{CER} - r_j)^2$$

1.12.3 Appendix 3. The Lucas Tree model:

Gollier (2001, p250) explains concisely the approach taken. The maximisation problem is a dynamic programme in which the equilibrium value function for individuals is:

$$v_t(y, b) = \max_{c_t} \{u(c_t) + \beta E v_{t+1}(y(1 + g_{t+1}), (1 + r_t)(c_t + b - y)) [u(\tilde{y}_t) | \tilde{y}_t = y]\}$$

where y is income (size of crop from trees) and b is repayment of debt (borrowed fruit). Commodities are assumed to be perishable and borrowing and lending occurs across time measured by the quantity $c_t + b - y$. Income y is exogenous but grows at the uncertain rate \tilde{g}_t , which is assumed to be *i.i.d* across time. The first order conditions for maximisation are:

$$u'(c_t) = -\beta E v'_{t+1}(y(1 + g_{t+1}), (1 + r_t)(c_t + b - y)) \quad (1.34)$$

Since all individuals are identical, the equilibrium in this economy is autarkic such that at time t the individual pays back any debt, b , and consumes such that $c = y - b$. There is no borrowing, hence $c_t + b - y = 0$. This means that the equilibrium value function at time t is:

$$v_t(y, b) = \max_{c_t} \left\{ u(c_t) + \sum_{\tau=t+1}^T \beta^{\tau-t} E[u(\tilde{y}_\tau) | \tilde{y}_t = y] \right\}$$

Hence the derivative of the value function with respect to the state variable b , is $v'_b = -u'(y - b)$, $v'_{t+1} = -u'(y(1 + \tilde{g}_{t+1}))$. Using these and rearranging (1.34) we obtain:

$$1 + r(c_t) = \frac{u'(c_t)}{\beta E[u'(c_t(1 + \tilde{g}_{t+1}))]}$$

Equation (1.25) can be found by first defining the *precautionary equivalent* growth rate \hat{g}_{t+1} as the certain growth rate that yields the same interest rate as in equation (1.24), that is:

$$\hat{g}_{t+1} : E[u'(y(1 + \tilde{g}_{t+1}))] = u'(y(1 + \hat{g}_{t+1}))$$

Taking second order Taylor series expansions of both sides yields:

$$\hat{g}_{t+1} = E\tilde{g}_{t+1} - \frac{1}{2} \text{var}(\tilde{g}_{t+1}) \frac{u'''}{u''} y$$

Inserting this into the Ramsey rule: $r = \rho + \theta g_{t+1}$ gives us (1.25).

Chapter 2

Time is the Healer: A resolution of the Gollier-Weitzman rift, or, just keep on discounting at a declining rate but.....

Abstract¹

The recent research described in Chapter 1 suggests that the long-term future should be discounted with a declining discount rate. One oft cited contribution to this literature is Weitzman (1998) who shows that when the discount rate is uncertain the socially efficient certainty equivalent rate is declining with the time horizon. As described in Chapter 1, Gollier (2004a) puts forward a puzzle that casts some doubt on the validity of this conclusion. He asserts that the using a Expected Net Future Value (ENFV) criterion rather than the conventional Expected Net Present Value (ENPV) criterion, implies that the certainty equivalent discount rate is in fact increasing over time. The presence of uncertainty in the discount rate makes the ENPV and ENFV criteria diverge in their prescription and the only way in which one can decide between these two criteria, Gollier argues, is by making a decision about whether present or future generations ought to bear the risk of the investment. Of course in a risk neutral environment this decision is always arbitrary.

This chapter resolves the apparent puzzle with a simple model which encompasses both Weitzman (1998) and Gollier (2004a). The model reveals that the mathematical result found by Gollier (2004a) is misinterpreted. Gollier (2004a) has in fact proved that as the evaluation date moves further into the future the discount rate at any particular point in time will increase. However, given a particular evaluation date, the schedule of discount rates for CBA is declining. The choice of either ENFV or ENPV as an evaluation criterion simply represents the choice of particular evaluation dates. The fact that this choice may lead to different assessments of the same project is simply another manifestation of time inconsistency described in Chapter 1. Given this the resolution of this puzzle generates some simple initial rules for CBA under uncertainty and in the face of time inconsistency.

¹This chapter is an extended version of a working paper entitled 'Gamma Discounting and Expected Net Future Value' which is joint work with Cameron Hepburn at St Hugh's College, Oxford..

2.1 Introduction

Section 1.4.2 of Chapter 1 described a puzzle within the literature on declining discount rates (DDRs) posed by Gollier (2004a) which has emerged from discussion of the work of Weitzman (1998, 2001). Weitzman (1998) provided a seemingly powerful argument for the use of declining discount rates based upon the uncertainty surrounding the discount rate itself: uncertainty in the discount rate itself leads to an arbitrage in which the socially efficient certainty equivalent discount rate is a declining function of time. The appeal of the argument has been such that subsequent work has endeavoured to operationalise the theory by determining the nature of the uncertainty surrounding the discount rate (Weitzman 2001, Newell and Pizer 2003). Indeed, the case for DDRs based on uncertainty has recently been accepted by the UK Government and is now incorporated into the Treasury Green book (HM Treasury 2003).

In a recent paper, Gollier (2004a) provides a simple argument which casts doubt on the validity of Weitzman's argument under uncertainty. Gollier argues that whether or not the certainty equivalent discount rate is declining or, by contrast, increasing depends entirely upon the evaluation criterion that one applies to a particular investment decision. While Weitzman (1998) considers the an Expected Net Present Value (ENPV) criterion when deriving the declining certainty equivalent rate, Gollier shows that if one maximises an Expected Net Future Value (ENFV) criterion, the resulting certainty equivalent rate is in fact increasing. In short the presence of uncertainty in the discount rate generates a divergence between the prescriptions of these two evaluation criteria, which does not exist under certainty.

Gollier's arguments leave the practitioner with a perplexing choice between his ENFV criterion and Weitzman's ENPV criterion, each of which polar to the other in its prescription for the schedule of social discount rates and, frequently, investment decisions. This leads Gollier (2004a) to state:

‘we cannot both be right.’

Gollier goes on to argue that choosing between the two criteria is akin to choosing the location in time of the risk associated with the investment: as we shall see below it is argued that the ENFV criterion places the risk with the future generations since the outcome of the compounding process is uncertain, while the ENPV criterion places the risk with the present

generation since the required level of investment is uncertain. Naturally, in the risk neutral environment of Weitzman, we cannot rely on economic arguments to guide us in this choice and ultimately, any decision is arbitrary. Gollier concludes:

‘In fact, to tell you the truth, I believe that we are both wrong’ (Gollier 2004a)

This paper argues to the contrary and shows that the ‘puzzle’ put forward by Gollier has a straightforward resolution which shows that there is a clear sense in which Weitzman (1998) and Gollier (2004a) *can* both be right. We demonstrate that the model in Gollier (2004a) does not prove that the discount rate increases with the passage of time. On the contrary, the socially efficient discount rate is declining irrespective of the criteria employed in CBA. However, we demonstrate that Gollier is correct in saying that the discount rate is increasing with one time variable. We prove that as the *evaluation date*, that is the numeraire date employed for assessing the investment, moves further into the future, the discount rate at a particular point in time increases. The latter is the insight discovered by Gollier (2004) and it is in this sense that both Gollier and Weitzman are both right.

The paper proceeds as follows. In Section 2.2 we describe the puzzle proposed by Gollier and present his argument that the certainty equivalent discount rate is increasing under the ENFV criterion. In Section 2.3 we discuss his explanation for the puzzle which is based upon the intertemporal allocation of risk and show in Section 2.4 that this interpretation is in fact incorrect. In Section 2.5 we explain that the puzzle arises simply from confusion as to the role of the *evaluation date*. In Section 2.6, we move beyond Gollier (2004a) and investigate the impact of the evaluation date upon the assessment of project viability. Having proven that the discount rate is a declining function of continuous time it is no surprise to find that decisions can be time inconsistent. That is, projects which are viable at one evaluation date may not be viable at later evaluation dates purely as a result of the passage of time. We develop some simple ‘intergenerational efficiency’ rules to determine how far into the future a given project would pass a CBA.

In Section 2.7 and 2.8 we investigate the importance of the nature of the probability distribution of discount rates for the schedule of discount rates and, more importantly the intergenerational efficiency criteria described in the previous Sections. This serves as an introduction to the work undertaken in Chapter 3. Section 2.9 concludes.

2.2 The Puzzle Once More

Gollier (2004a) describes the puzzle in terms of a simple project whose net benefits at time t , $B(t)$, accrue within the time period $t \in [0, T]$. The project requires an investment of £1 at time $t = 0$ in order to reap a certain return £ Z at time $t = T$. Following Weitzman (1998) the social opportunity cost of investment is assumed to be the random variable, \tilde{r} , which has cumulative distribution function $F(r)$, probability density function $f(r)$, and support $r \in [r_{\min}, r_{\max}]$. This leads to Definition 1:

Definition 1 (A Gollier Project):

A ‘Gollier project’ is one which has a the flow of net benefits given by the step function²:

$$\dot{B}(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ -1 & \text{for } 0 < t < T \\ Z & \text{for } t \geq T \end{cases}$$

The initial discussion looks at a Gollier project, although later more general projects and investments are considered.

2.2.1 Expected net present value (ENPV)

The ENPV of an investment is found by converting all cash flows into common units at $t = 0$. This entails multiplying the net benefits flows, $B(t)$, by the certainty equivalent discount factor as defined in Chapter 1. We reproduce this definition here for the case where $f(r)$ is not dependent on time:

$$A(t) = \mathbf{E} \exp(-\tilde{r}t) = \int_{r_{\min}}^{r_{\max}} \exp(-\tilde{r}t) f(r) dr \quad (2.1)$$

Therefore *ENPV* can be defined as³:

$$ENPV = \int_{r_{\min}}^{r_{\max}} \int_0^T \exp(-\tilde{r}t) d\dot{B}(t) f(r) dr = \int_0^T A(t) d\dot{B}(t) \quad (2.2)$$

²I thank my examiners for alerting me to this approach which circumvents the fact that without this definition the integral of the project values over time is undefined. This approach means that the expected net present value of a Gollier project becomes: $ENPV = \int_{r_{\min}}^{r_{\max}} \int_0^T \exp(-\tilde{r}t) d\dot{B}(t) f(r) dr = \int_0^T A(t) d\dot{B}(t) = E(-\exp(r\tau) + \exp(r(T-\tau)).Z$ as desired.

³Given definition 1 we choose this definition as opposed to: $NPV = \int_{r_{\min}}^{r_{\max}} \int_0^T B(t) \exp(-\tilde{r}t) dt f(r) dr = \int_0^T B(t) A(t) dt$, which is also valid except for instantaneous costs and benefits like those of the Gollier project.

Weitzman's certainty equivalent rate defines the discount rate that should be used when the objective is to maximise the Expected Net Present Value (ENPV) of investments given uncertainty in the interest rate⁴. Applying definition 1 to (2.2) means that we are comparing the return to an investment of £1 with fixed future benefit of £Z in year T, to an alternative investment with a random rate of return, \tilde{r} . The planner will rank these alternatives by calculating the ENPV. In the case of definition 1, and following Gollier (2004a) the ENPV rule can be represented by:

$$ENPV : ZE[\exp(-\tilde{r}T)] - 1 \geq 0 \quad (2.3)$$

If this condition holds, then the agent should proceed with the project. Given that maximising ENPV is the objective, and using (2.1), the (average) certainty equivalent per period discount rate in this environment can be defined as r^{PV} :

$$\exp(-r^{PV}t) = E[\exp(-\tilde{r}t)] \quad (2.4)$$

$$\implies r^{PV} = -\frac{1}{t} \ln[E[\exp(-\tilde{r}t)]] \quad (2.5)$$

This is simply a restatement of equation (1.20) in Chapter 1. This leads to proposition 1:

Proposition 1 (ENPV leads to declining discount rate) : *The average certainty equivalent rate under ENPV rule, r^{PV} , is declining starting from an initial point $E\tilde{r}$ and converging to the lower bound r_{\min} as t tends to infinity.*

Proof. (Gollier 2004a) r^{PV} defined in (2.4) can be seen as the certainty equivalent of the random payoff \tilde{r} for an agent with a constant absolute risk aversion measured by t where the utility function is $-e^{-r^{PV}t}$. An increase in the value of t can therefore be interpreted as a increase in the degree of risk aversion. In this context it is well known (see e.g. Pratt 1964) that r^{PV} tends to the lower bound of the support of \tilde{r} , that is, r_{\min} . L'Hôpital's rule, taking limit of r^{PV} as $t \rightarrow 0$, can be used to show that the schedule begins at $E\tilde{r}$. ■

2.2.2 Expected Net Future Value (ENFV)

Alternatively, imagine that we want to maximise the expected net future value (ENFV), i.e. we wish to rank our projects on the basis of maximising the value of assets that accumulate

⁴Here we are referring to the average certainty equivalent rate as described in equation (16) in chapter 1. This is not important for the analysis that follows.

to future generations. This is done by converting all future cash flows into common units at a future point in time, usually the project end date; $t = T$. This conversion is done by multiplying cash flows as and when they occur by a suitably adjusted certainty equivalent discount factor defined as:

$$A(t, T) = \mathbf{E} \exp(-\tilde{r}(t - T)) = \int_{r_{\min}}^{r_{\max}} \exp(-\tilde{r}(t - T)) f(r) dr \quad (2.6)$$

The ENFV rule can be thought of as:

$$ENFV = \int_{r_{\min}}^{r_{\max}} \int_0^T \exp(-\tilde{r}(t - T)) d\dot{B}(t) f(r) dr = \int_0^T A(t, T) d\dot{B}(t) \quad (2.7)$$

and applying definition 1 we get the *ENFV* criteria:

$$ENFV : Z - 1E[\exp(\tilde{r}T)] \geq 0 \quad (2.8)$$

In this case the certainty equivalent per period interest rate, r^{FV} , that produces the same outcome as the random interest rate is that which satisfies:

$$\exp(r^{FV}t) = E[\exp(\tilde{r}t)] \quad (2.9)$$

$$\implies r^{FV} = \frac{1}{t} \ln[E[\exp(\tilde{r}t)]] \quad (2.10)$$

That is, maximising the ENFV criteria is equivalent to assessing the ENPV using r^{FV} as the discount rate. A comparison of (2.4) and (2.10) shows clearly that, $r^{PV} \neq r^{FV}$. Furthermore, it is easy to show that r^{FV} is increasing over time. This leads to Proposition 2:

Proposition 2 (ENFV leads to increasing discount rate) : *Gollier's certainty equivalent average discount rate under ENFV, r^{FV} is increasing over time starting at $E\tilde{r}$ at $t = 0$ and converging to the upper bound, r_{\max} , as t tends to infinity.*

Proof. The proof of this proposition is the dual of the proof of proposition 1. All that is required is a change in the interpretation of the parameters. In this case we define r^{FV} as the certainty equivalent of a random payoff \tilde{r} for an agent with constant absolute risk aversion measured by $-t$. As risk aversion decreases, that is as t increases, the certainty equivalent r^{FV} tends to the maximum value on the support of \tilde{r} . That the schedule starts at $E\tilde{r}$ is again given by L'Hôpital's rule. ■

So, confusingly, although the two decision criteria ought to be equivalent, as is the case under certainty, once uncertainty regarding the discount rate is introduced the appropriate discount rate for use in CBA depends upon the choice of ENPV or ENFV as our decision criterion. In the former case discount rates are declining and correspond to Weitzman (1998), and in the latter they are rising through time. Clearly, each criteria is likely to provide radically different prescriptions for any given project. It is therefore important that we gain some understanding as to which of these criteria is preferable and what we are trading off when we choose one method over the other. We now examine the solution provided by Gollier (2004a).

2.3 Gollier's Explanation: Risk allocation

Gollier (2004a) explains that choosing between the two criteria implies different and arbitrary allocations of investment risk. He states:

‘taking the expected future value is equivalent to assuming that all risks are borne by the future generation...Using the expected present value implicitly means it is the current generation that bears the risk. Because the two approaches lead to radically different recommendations, we see that, to solve the problem we cannot escape the discussion of who should bear the risk.’

On the face of it, the logic behind this statement is as follows. Using the ENPV criteria appears to locate investment risk with the current generation (strictly, $t = 0$) since, once the discount rate is realised the NPV may or may not be positive. Since the payoff in the future (Z) is certain, any residual losses appear to be borne by the present generation. In effect the current generation debates whether or not to secure a certain payoff for future generations at the cost of a random payment in the present (Gollier 2002a). For example, if the ENPV equalled zero, but the realised discount rate, say R , is greater than the certainty equivalent rate: $R > r^{PV}$, the project is not viable ex post, and investors must internalise any opportunity cost. The symmetric argument to this is the case where ENPV is negative and the realisation of R is such that the ex post NPV is in fact positive.

On the other hand, that using ENFV implies that future generations bear the risk appears to follow from the fact that the current generation makes a certain contribution to the project (£1), but the rate at which funds accumulate on the market is uncertain before the realisation of the discount rate. Any shortfall appears to be borne by the future.

Consequently, so the argument goes, choosing between these two decision criteria under uncertainty appears to be solely a question of the temporal allocation of risk. Gollier argues further that, given the risk neutral environment, we cannot appeal to economic arguments to make this decision: with risk neutrality the optimal temporal allocation of risk is undefined and hence any decision is arbitrary. He asserts that in order to make this judgement one must undertake an explicit treatment of risk preferences, such as that developed in Gollier (2002a, 2002b, 2004b) as described in Section 1.4.3 of Chapter 1.

2.4 The Critique of Gollier (2004a)

Despite this puzzling conclusion, Gollier's explanation has some intuitive appeal given the apparent logic outlined above. That is, until one looks a little closer. Gollier appears to conclude that in a risk-neutral environment the allocation of risk is pivotal to our definition of the socially efficient discount rate for CBA. That is, assumptions concerning risk can alter the decisions of a risk-neutral investor. The more one thinks about this state of affairs the less intuitive the conclusion sounds.

Not only does this trouble our intuition, the idea that different decision criteria imply entirely different temporal allocations of risk is patently false. In short, the logic described above is incomplete. To see this imagine the following two thought experiments.

Example 1: (Risk for future generations) Suppose one has £1 to invest and one must choose between 2 options (1) a safe deposit with a certain return, r , yielding a payoff of e^{rT} after T years; or (2) the market, with a stochastic return of \tilde{r} , with expected payoff at time T of $E\exp(\tilde{r}T)$. If the safe deposit yields 3% the payoff is £400 in $T = 200$ years. If the market is equally likely to return 0% or 5%, the payoff is either £1 or £22,000 respectively in 200 years. A risk-neutral investor employing the ENFV criterion would clearly choose the risky investment: the market, while the same investor would choose the safe investment: the safe deposit, when employing the ENPV criterion. This can be seen by comparing the numerical

values of each investment under each criterion. Firstly consider the ENPV criteria:

$$\begin{aligned}
 ENPV_{Deposit} &\approx -£1 + £400 \left[\frac{1}{2} \cdot e^{-(0 \cdot 200)} + \frac{1}{2} \cdot e^{-(.05 \cdot 200)} \right] \\
 &\approx £199 \\
 ENPV_{Market} &\approx -£1 + \frac{1}{2} \cdot £1 e^{-(0 \cdot 200)} + £22,000 \frac{1}{2} \cdot e^{-(.05 \cdot 200)} \\
 &\approx £0
 \end{aligned}$$

Now consider the ENFV criteria used to evaluate the same project:

$$\begin{aligned}
 ENFV_{Deposit} &\approx -£1 \left[\frac{1}{2} e^{0 \cdot 200} + \frac{1}{2} e^{.05 \cdot 200} \right] + 400 \\
 &\approx -£10,600 \\
 ENFV_{Market} &\approx -£1 + £1 * \left[\frac{1}{2} e^{0 \cdot 200} + \frac{1}{2} e^{.05 \cdot 200} \right] \\
 &\approx £11,000
 \end{aligned}$$

In this example it should be clear that the uncertainty surrounding the investment is borne by the future generations irrespective of the decision criteria employed.

Example 2: (Risk for current generation) Suppose it is desired to have a certain payoff of $Z = e^{rT}$ at time T and one can choose between two options: (1) invest £1 in a safe deposit yielding a certain payoff of $£Z = e^{rT}$ after T years; or (2) purchase a bond on the market which pays $£Z$ for certain with maturity in T years. The current price of the bond depends upon the market interest rate, \tilde{r} , and we suppose that bond is purchased before the interest rate is known. The expected bond price is therefore $£Z Ee^{(-\tilde{r}T)}$ and with the same numbers as above is equally likely to be £400 or £0.02: approximately £200. As before a risk neutral investor employing the ENPV criterion would invest in the safe deposit whereas the same investor would choose the market if employing the ENFV criterion. Once more this can be seen by considering the numerical example explicitly:

Firstly consider the ENPV criteria:

$$\begin{aligned}
 ENPV_{Deposit} &\approx -£1 + £400 \left[\frac{1}{2} e^{-(0 \cdot 200)} + \frac{1}{2} e^{-(.05 \cdot 200)} \right] \\
 &\approx £199 \\
 ENPV_{Market} &= -£400 * \left[\frac{1}{2} e^{-(0 \cdot 200)} + \frac{1}{2} e^{-(.05 \cdot 200)} \right] \\
 &\quad + £400 \left[\frac{1}{2} e^{-(0 \cdot 200)} + \frac{1}{2} e^{-(.05 \cdot 200)} \right] \\
 &\approx £0
 \end{aligned}$$

Table 2.1: Two thought experiments on decision criteria and risk allocation.

Criterion	Future bears risk	Present bears risk
ENPV	Safe deposit	Safe deposit
ENFV	Market	Market

Now consider the ENFV criteria used to evaluate the same project:

$$\begin{aligned}
 ENFV_{Deposit} &= -\mathcal{L}1 \left[\frac{1}{2}e^{0*200} + \frac{1}{2}e^{.05*200} \right] + 400 \\
 &\approx -\mathcal{L}10600 \\
 ENFV_{Market} &= -\mathcal{L}400 * \left[\frac{1}{2}e^{-(0*200)} + \frac{1}{2}e^{-(.05*200)} \right] + 400 \\
 &\approx \mathcal{L}200
 \end{aligned}$$

In this example it should be clear that the uncertainty surrounding the investment is borne by the current generation irrespective of the decision criteria employed.

These two thought experiments, the outcome of which is summarised in Table 2.1 show that Golliers explanation is not entirely correct. Example 1 imposes investment risk on future generations since the outcome of the market investment is inherently risky yet the required investment is certain. Example 2 imposes investment risk upon the current generation, since although the outcome of the investment is certain, the contribution required in the market is uncertain.

Both evaluation criteria were applied in example 1 and 2 and it is clear that the allocation of risk did not change the outcome, only the selection of the criterion itself is of any moment. These thought experiments serve to disentangle the allocation of investment risk from the decision criteria. They show that the temporal allocation of risk is a feature of the investment or project itself, not of the criteria by which it is evaluated. In sum, using the ENFV criterion the decision maker will always prefer the risky market options, while using an ENPV criterion will lead the decision maker to prefer the certain safe deposit option. More generally, the ENFV criterion leads to higher risk investments being chosen in the case of Gollier projects. This is the case *no matter which generation bears the risk*.

As a result it becomes clear that Gollier's explanation for the divergent outcomes of ENFV and ENPV decision criteria based on the allocation of risk does not solve the puzzle concerning

how to choose among decision criteria. In what follows we show that consideration of the evaluation date is more fruitful.

2.5 An Alternative Explanation: Evaluation date

Up until this point we have considered either ENPV or ENFV criteria. The former effectively evaluates the project from the perspective of a decision maker at $t = 0$ while the latter evaluates from the perspective of a decision maker at time $t = T$. From hereon we say that the ‘evaluation date’ for ENPV and ENFV criteria is 0 and T respectively. Moreover, we generalise the analysis to take explicit account of any potential evaluation date, τ , by defining the ‘Expected Net Value’ at evaluation date τ as $ENV(\tau)$:

$$ENV(\tau) = \mathbf{E} \int_0^T \exp(-\tilde{r}(t - \tau)) d\dot{B}(t) \quad (2.11)$$

Note that the $ENV(\tau)$ criterion incorporates both the ENPV and ENFV criteria. We obtain the former by setting $\tau = 0$ and the latter by setting $\tau = T$. This can be seen by reference to (2.2) and (2.7). $ENV(\tau)$ is completely general in this sense.

Analogously to the definition of the certainty equivalent discount functions defined in equation (2.1) and (2.6) we can define the certainty equivalent discount function associated with this evaluation criterion:

$$A(t, \tau) = \mathbf{E} \exp(-\tilde{r}(t - \tau)) \quad (2.12)$$

The discount function is normalised to unity at time $t = \tau$ ⁵. From this we obtain the certainty equivalent average discount rate:

$$\begin{aligned} \exp(-r^{NV}(t, \tau)(t - \tau)) &= \mathbf{E} \exp(-\tilde{r}(t - \tau)) \\ \implies r^{NV}(t, \tau) &= -\frac{1}{t - \tau} \ln(A(t, \tau)) \end{aligned} \quad (2.13)$$

This leads to the following proposition:

⁵Other normalisations are also valid but the results that follow do not depend upon the particular normalisation. Thanks to Christian Gollier for alerting us to this point.

Proposition 3 *The certainty equivalent average discount rate, $r^{NV}(t, \tau)$, declines with the passage of time, t , to $\lim_{t \rightarrow \infty} r^{NV}(t, \tau) = r_{\min}$, but is **increasing** with the evaluation date, τ , to $\lim_{\tau \rightarrow \infty} r^{NV}(t, \tau) = r_{\max}$. Furthermore, $\lim_{t \rightarrow \tau} r^{NV} = \mathbf{E}\tilde{r}$.*

Proof. It was proved in proposition 1 that the certainty equivalent average rate, r^{PV} , is declining with t and this proof is sufficient for $r^{NV}(t, \tau)$. The proof that $r^{NV}(t, \tau)$ is increasing in the evaluation date τ follows simply from the fact that $\frac{\partial r^{PV}}{\partial t} = -\frac{\partial r^{PV}}{\partial \tau}$. That $\lim_{t \rightarrow \tau} r^{NV} = \mathbf{E}\tilde{r}$ follows from taking limits and using L'Hôpital's rule. ■

Proposition 2 immediately suggests where Gollier may have erred. Although the discount rate is declining with t it is increasing in the evaluation date, τ . Gollier appears to have confused these two different time variables. To make this concrete let us reconsider Gollier's the certainty equivalent average discount rate defined in equation (2.10). The generalised expression for the discount rate shown in (2.13) above shows that when $\tau = T$, that is, when we consider an ENFV criterion, cash flows at time t must be discounted using the discount function $\mathbf{E}\exp(-\tilde{r}(t - T))$, and the certainty equivalent average discount rate is given by:

$$r^{NV}(t, T) = -\frac{1}{t - T} \ln \mathbf{E} \exp(-\tilde{r}(t - T)) \quad (2.14)$$

This equation should be identical to (2.10), but clearly this is not the case. Gollier's specification of the certainty equivalent average discount rate is incomplete. This is most easily seen when evaluating (2.14) at $t = 0$:

$$r^{NV}(0, T) = \frac{1}{T} \ln (\mathbf{E} e^{\tilde{r}T}) \quad (2.15)$$

which is almost identical to equation (2.10) save for one thing. The evaluation date $\tau = T$ in (2.15) has been replaced by the passage of time t in Gollier's expression in (2.10).

It is in this sense that both Weitzman and Gollier can be right. Firstly, the certainty equivalent discount rate is declining with the passage of time in a manner virtually identical to that described by Weitzman (1998). Secondly, Gollier is correct to say that the certainty equivalent discount rate is increasing in one time variable, it is simply that he has the wrong time variable. The discount rate is an increasing function of the *evaluation date*, not the passage of time.

Figure 2.1 illustrates the crux of the issue. For a given evaluation date, τ , the certainty equivalent discount rate declines as time t increases. However, the schedule of certainty equiv-

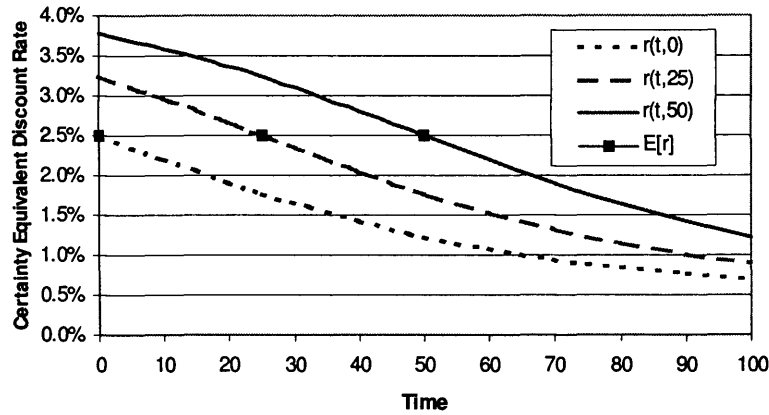


Figure 2.1: Discount rate schedules for three evaluation dates.

alent average discount rates shifts upwards as the evaluation date τ moves further into the future. This is, in fact, the result proved by Gollier (2004) and his expression for r^{FV} effectively describes how the discount rate at a particular point in time increases with the evaluation date τ . In conclusion therefore we have proved that the certainty equivalent discount rate is declining with the passage of time regardless of whether decision-makers employ ENFV, ENPV or $ENV(\tau)$ as their evaluation criterion.

2.6 Project Efficiency and the Evaluation Date

Recall that the original puzzle highlighted by Gollier (2004a) stemmed from the fact that the viability of an investment would depend upon the evaluation criterion employed. For example, a project that passed a cost benefit analysis using the ENPV criterion may fail when using the ENFV criterion. Given the foregoing this puzzle can now be translated into the following statement: why is it that, when the discount rate is uncertain, the viability of a project will differ depending upon the evaluation date τ ?

The answer to this is well known in the literature and has been discussed in Section 1.7.3 of Chapter 1. Using declining discount rates can lead to time inconsistency, that is, decisions made at one point in time may be reversed when evaluated at some later date for no other reason than the passage of time⁶. Where the discount rate is declining through time as described above, the

⁶See section 1.7.3 of Chapter 1 for a discussion of these issues.

rate of discount applied at any point in time will depend upon the evaluation date τ^7 . Thus a project that passes a cost benefit analysis from the perspective of a planner at evaluation date τ_1 may fail a test from the perspective of a planner at evaluation date τ_2 . Consequently, the puzzle posed by Gollier (2004a) is not a puzzle at all, it is simply another manifestation of time inconsistency arising from the use of declining discount rates in CBA.

Having said this, the time inconsistency that we find in this case is of a different nature to that usually seen in the literature. Usually time inconsistency arises due to non-constant utility discount rate. Time consistent planning, a constant utility discount rate and a time varying consumption discount rate can and do frequently coexist. In the Weitzman model, however, there is no underlying optimisation model to determine the consumption discount rate, it is taken as given, and so time inconsistency is unavoidable even if there is a constant utility discount rate. Furthermore, time inconsistency usually involves a planner arriving at a particular point in time in the *future* and finding that a ascribed-to plan is no longer optimal *purely because of the passage of time*⁸. In the case in hand we are considering a planner conducting a thought experiment *today* concerning how some future planner would behave *today* given the same investment opportunities. In our case time inconsistency occurs when the current planners view of the efficiency of an investment today differs from the current planners projection of the future planner's view of the efficiency of the investment today, given the different schedule of discount rates applied by the future planner (at the future evaluation date). That is, time inconsistency occurs when the an investment today is found to be efficient from the perspective of one evaluation date and inefficient from the perspective of another.

With the puzzle solved and with some understanding of economic theory behind the results in Gollier (2004a) it remains to address some of the practical issues surrounding time inconsis-

⁷Heal (1998) describes the exceptions.

⁸Newell and Pizer (2003) discuss this issue at some length and claim that where uncertainty is driving the decline in discount rates, erring from the previously optimal plan upon the arrival of new information does not represent time inconsistent behaviour, but merely changing behaviour in light of the best available information. Of course, naively using the fixed/deterministic schedule of certainty equivalent discount rates that emerges from their analysis and that of Weitzman's may still result in time inconsistency. Furthermore, it is not entirely clear that arrival of new information concerning the discount rate will always alter the Newell and Pizer's certainty equivalent rate schedule, although the passage of time may induce changes in behaviour where the same discount schedule is used. It is therefore debatable, in the authors opinion, whether their suggestion that time inconsistency is entirely avoided in the presence of uncertainty always holds true.

tency⁹. The following questions arise: How can decision makers deal with time-inconsistency when conducting CBA under uncertainty? Is it possible to develop some recommendations for CBA that take into account the presence of time inconsistency? The following Section takes up these questions.

2.6.1 Time inconsistency and critical evaluation dates

If a project designed for the benefit of future generations passes a cost benefit analysis now, but would fail the same test when using a later evaluation date, should we invest in this project? Or, more generally, how do we overcome the conflicting results of CBA undertaken using different evaluation dates? Which date is more important?

In this Section we propose an answer to these questions. We begin by defining the internal rate of return of the project as the constant certain rate of return that yields a zero Net Value ($NV(\tau, r)$). Define the $NV(\tau, r)$ and internal rate of return of a project $B(t)$ as follows:

Definition 2. (Net Value ($NV(\tau, r)$)):

$$NV(\tau, r) = \int_0^T B(t) \exp(-r(t - \tau)) dt \quad (2.16)$$

For a Gollier project (see definition 1) $NV(\tau, r) = e^{r\tau} [Ze^{-rT} - 1]$.

Definition 3. (Internal Rate of Return: r^*): The internal rate of return of a project is $r^* = \{r : NV(\tau, r) = 0\}$. For a Gollier project $(Z, T) = (400, 200)$, $r^* = \frac{1}{T} \ln Z = 3\%$.

In addition, the following definition is useful:

Definition 4. (Critical Evaluation Date: τ^*): The critical evaluation date of a project is $\tau^* = \{\tau : ENV(\tau) = 0\}$. For the Gollier project described in example 1 and 2 above for which $(r_1, p_1, r_2, p_2, Z, T) = (0\%, 0.5, 5\%, 0.5, 400, 200)$, $\tau^* = \frac{1}{r_1 - r_2} \left[\ln \left[\frac{1 - Z \exp(-r_2 T)}{Z \exp(-r_1 T) - 1} \frac{p_2}{p_1} \right] \right] \approx 120$.

⁹The time inconsistency here is slightly unusual however. Usually, time inconsistency involves a planner at a future date finding it optimal to deviate from an earlier plan. That is the planner today and the future planner disagree about the optimal *future* action. Here, however, the planner today and the future planner disagree about the optimal action *today*. That is there is a divergence between what the future planner would like the current planner to do and what the current planner considers to be optimal.

Furthermore, since the efficiency of a project is assessed differently from the perspective of different evaluation dates, τ , we shall say that a project is τ -efficient if it passes a CBA at evaluation date τ . Armed with these definitions we can make the following proposition:

Proposition 4 (Future efficiency implies present efficiency) : *For the set of projects with $cov(\tilde{r}, NV(\tau, \tilde{r})) < 0$, if the project is τ' -efficient then it is also τ -efficient for $\tau' \geq \tau$.*

Proof. Differentiating equation (2.11) with respect to the evaluation date we see that:

$$\begin{aligned} \frac{dENV(\tau)}{d\tau} &= E\tilde{r} \int_0^T B(t) \exp(-\tilde{r}(t - \tau)) dt \\ &= E[\tilde{r}.NV(\tau, r)] \\ &= E\tilde{r}.ENV(\tau) + cov(\tilde{r}, NV(\tau, r)) \end{aligned} \tag{2.17}$$

It is reasonable to assume, as in the numerical examples, that $E\tilde{r} > 0$. Indeed this holds whenever an investment has a positive opportunity cost. It follows from (2.17) that $ENV(\tau) < 0 \implies dENV(\tau)/d\tau < 0$, so if $ENV(\tau) = 0$, then $ENV(\tau') < 0$ for all $\tau' > \tau$. The corollary of this is that if $ENV(\tau') = 0$, then $ENV(\tau) > 0$ for all $\tau < \tau'$. ■

Note that Proposition 2 implies that to investments with $cov(\tilde{r}, NV(\tau, \tilde{r})) < 0$, that is, where a higher discount rate produces a lower net value¹⁰. Most investments fit into this category because an ‘investment’ by definition involves costs now in return for benefits in the future. However, some investments also have costs which accrue after an initial investment and a long stream of benefits, such as nuclear power plants. The net value of such projects is increasing in \tilde{r} over some range of and hence $cov(\tilde{r}, NV(\tau, \tilde{r}))$ may in fact be positive. In these cases the internal rate of return (IRR) of the project is not necessarily unique. Appendix 1 provides some illustrative examples of the possibilities here. Despite this possibility, proposition 2 holds for a larger set of projects than those with a unique internal rate of return and $NV(\tau, r)$ monotonically decreasing in r . This is because $cov(\tilde{r}, NV(\tau, \tilde{r}))$ may be negative even if the $NV(\tau, r)$ is increasing over a subset of the domain.

¹⁰ As such, proposition 2 holds for all Gollier projects assuming there exists a $\tau : ENV(\tau) = 0$, and $NV(\tau) < 0$ when evaluated at \tilde{r} .

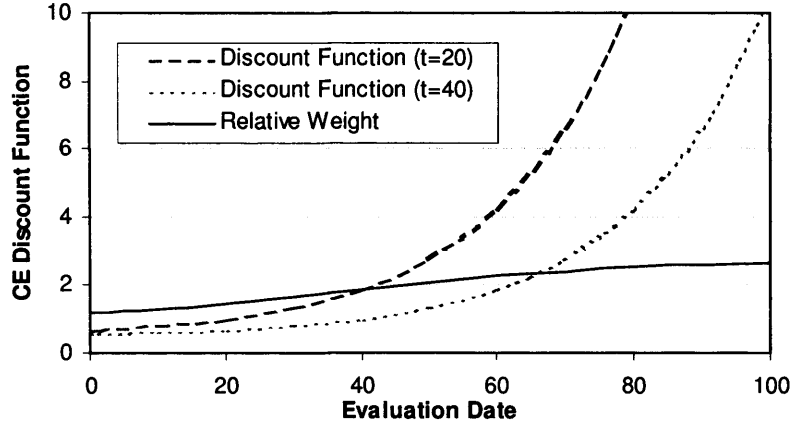


Figure 2.2: Relative weight on early cash flows increases with evaluation date τ .

This result effectively generalises the finding in Section 2.4, summarised in Table 2.1, in which it was shown that the ENPV criterion consistently preferred the certain investment whereas the ENFV criteria consistently preferred the risky market investment. Proposition 4 shows that if the future generation finds a safe investment to be efficient, relative to the risky market alternative, then the present generation will also judge the safe investment efficient. However, the converse is not true: even if the present generation finds the safe investment to be efficient, the future generations may judge the risky investment to be efficient. Moreover, given definition 4, proposition 4 tells us that a project is efficient for all $\tau \leq \tau^*$.

Mathematically this result arises since, as the evaluation date moves further into the future, the weight placed upon costs and benefits that accrue earlier in time. Given the nature of the investment project that we have considered so far, that is, costs are incurred in the first instance and the benefits accrue later, the reversal of the judgement of efficiency comes about because of the ever increasing weight attached to the initial investment costs. Figure 2.2 shows that as $\tau - t$ increases in value, the investment costs are compounded forward quicker than the benefits and $ENV(\tau)$ is diminished¹¹.

¹¹It should be noted that the normalisation of the discount function is not important in this regard since it does not change the relative weights between costs and benefits accruing in different time periods.

2.6.2 Intergenerational rules for Cost Benefit Analysis

Clearly, the value of τ^* is of interest to the decision-maker since it tells her the extent to which projects will remain efficient once evaluated from the perspective of future generations¹². In essence it says something about the extent to which there will be an intergenerational consensus with regard to a project. In this way, the decision maker can make an initial assessment as to the extent to which time inconsistency is likely to be a problem. It follows from this that we can determine the conditions under which a project will be (1) efficient for all evaluation dates, that is τ^* is unbounded; (2) efficient for all evaluation dates up to the end of the project (the payoff date T), that is, $\tau^* > T$; (3) efficient at the current date, that is $\tau^* > 0$; and, for completeness; (4) unanimously inefficient, that is never efficient not even for dates in the past, (as τ^* tends to negative infinity). Cases (1) and (4) imply an absence of intergenerational conflict. We first do this by looking at Gollier projects.

With a certain discount rate, definition 1 implies that the $ENV(\tau)$ of any flow of benefits $B(t)$ the same as the flow of benefits given by:

$$B(t) = \begin{cases} -1 & \text{for } t = 0 \\ e^{r^*T} & \text{for } t = T \\ 0 & \text{otherwise} \end{cases}$$

where r^* is the internal rate of return. Under uncertainty, the expected net value of the set of Gollier projects that yield $Z = e^{r^*T}$ becomes:

$$ENV(\tau) = \mathbf{E} \left[e^{\tilde{r}\tau} \left(e^{(r^* - \tilde{r})T} - 1 \right) \right] \quad (2.18)$$

Since $e^{-\tilde{r}\tau} > 0$, it follows that for all Gollier projects¹³ if r^* exceeds r_{\max} then $e^{(r^* - \tilde{r})T} > 1$ for all realisations of \tilde{r} , and hence $ENV(\tau)$ is certainly greater than zero for all τ . In other words, if the internal rate of return of the project exceeds the upper bound of the support of the discount rate then all generations are unanimous in their judgement of the efficiency of the project. We shall say that a project for which $r^* > r_{\max}$ is unanimously efficient. Of course, this is entirely intuitive: if the certain project has a payoff that is exceeding the best possible outcome on the markets, all generations will prefer the certain project.

¹²In undertaking this evaluation we are asking the current generation to imagine how the future generation would evaluate the project were it able to make the decision in the present.

¹³Indeed, for all investment projects with a unique internal rate of return.

In the foregoing we have highlighted the possibility of time inconsistency in the presence of declining discount rates. That is, projects are likely to exist for which the judgement will be less than unanimous across generations. Naturally it is possible to define weaker efficiency rules in such situations. For example, we may be interested in determining whether or not a project is considered efficient over its time horizon $[0, T]$. Given proposition 4 this effectively means assessing whether or not $ENV(T) \geq 0$. If this is so then let us call this *time horizon efficient*. Similarly, we may want to apply the test of whether or not $ENV(0) \geq 0$, that is, is the project at least efficient from the perspective of the present day. If so then let us call this project *currently viable*.

Finally, we can observe from (2.18) that if $r^* < r_{\min}$ then $ENV(\tau) < 0$ for all τ . Again this is intuitive: if the rate of return from the certain project is lower than the lowest possible return from the market then the project is *unanimously inefficient*. In sum, this discussion leads to the following proposition:

Proposition 5 (Intergenerational Efficiency Rules) : *A Gollier project with internal rate of return r^* is said to be:*

$$\left\{ \begin{array}{l} \text{unanimously efficient} \\ \text{time horizon efficient} \\ \text{currently efficient} \\ \text{unanimously inefficient} \end{array} \right\} \text{ for } \left\{ \begin{array}{l} r^* > r_{\max} \\ r^* > r^{NV}(0, T) \\ r^* > r^{NV}(T, 0) \\ r^* < r_{\min} \end{array} \right.$$

Proof. The unanimously efficient and time horizon efficient cases were proved in relation to (2.18) above. For the other two cases consider a Gollier project with payoff Z at time T . The project is τ -efficient if $Z > \bar{Z}$ where \bar{Z} is the payoff that implies that $ENV(\tau) = 0$, that is:

$$\bar{Z}(\tau) = \frac{Ee^{\tilde{r}\tau}}{Ee^{-\tilde{r}(T-\tau)}} \quad (2.19)$$

For the project to be time horizon efficient, that is for the project to be T -efficient, equation (2.19) requires that the payoff Z must exceed $\bar{Z}(\tau) = Ee^{\tilde{r}\tau}$. The internal rate of return of a T -efficient project is given by $\frac{1}{T} \ln \bar{Z} = \frac{1}{T} \ln Ee^{\tilde{r}T} = r^{NV}(0, T)$. Thus any project with an internal rate of return $r^* > r^{NV}(0, T)$ is time horizon efficient.

For a project to be currently efficient requires that Z exceeds $\bar{Z}(0) = 1/Ee^{-\tilde{r}T}$. The internal rate of return for the marginal project is $-\frac{1}{T} \ln Ee^{-\tilde{r}T} = r^{NV}(T, 0)$. Thus a project with internal rate of return $r^* > r^{NV}(T, 0)$ is currently efficient and has $ENPV > 0$. ■

The intergenerational efficiency rules in proposition (5) represent a first step towards dealing with the intergenerational conflict arising from declining discount rates. Clearly, policy-makers can invest with confidence in a project that is unanimously efficient, and they would probably be comfortable investing in projects that are time-horizon efficient. For short-term projects, the simple requirement of current efficiency might be enough. With the recent policy focus on ensuring ‘sustainability’, however, perhaps this sets the bar too low, but ultimately, this is for governments to decide.

2.7 Project Efficiency and Discount Rate Uncertainty

The previous Section demonstrated that once the evaluation date, τ , moves past the critical evaluation date, τ^* , a safe investment will no longer be considered efficient (when compared to a risky market numeraire). The time inconsistency created by declining discount rates implies that (risk-neutral) future generations would assess a safe project less favourably than (risk-neutral) current generations.

This Section asks whether an increase in the level of background uncertainty in economy — represented by discount rate uncertainty — changes the critical evaluation date for the safe project. Given the results above, we might expect that greater uncertainty in the economy will make the certain project less attractive to future generations, moving the critical evaluation date earlier in time.

To determine the impact of discount rate uncertainty on τ^* , we suppose that the discount rate is drawn from a gamma distribution with density function:

$$f(r) = \frac{\beta^\alpha}{\Gamma(\alpha)} r^{\alpha-1} e^{-\beta r} \quad (2.20)$$

For a Gamma distribution, the mean is $\mu = \alpha/\beta$ and the variance is $\sigma^2 = \alpha/\beta^2$. Using this fact, it is straightforward to show, as per Sozou (1998) and Weitzman (2001), that the certainty-equivalent discount function is:

$$D_c(t, \tau) = \left(1 + \frac{(t - \tau)\sigma^2}{\mu} \right)^{\frac{-\mu^2}{\sigma^2}} \quad (2.21)$$

where the condition $\tau < t + \mu/\sigma^2$ ensures that the discount function is nonnegative. This restriction implies that as the variance in the discount rate becomes large, the domain of permissible evaluation dates becomes increasingly small. The certainty-equivalent marginal

discount rate is:

$$r_{cm}(t, \tau) = \frac{\mu}{1 + \frac{(t-\tau)\sigma^2}{\mu}} \quad (2.22)$$

And the certainty-equivalent average discount rate is:

$$r_{ca}(t, \tau) = \frac{\mu^2}{\sigma^2(t-\tau)} \log \left(1 + \frac{(t-\tau)\sigma^2}{\mu} \right) \quad (2.23)$$

When the discount rate follows a gamma distribution, setting $ENV(\tau) = 0$ for a Gollier project yields the critical evaluation date to be:

$$\bar{\tau} = \frac{\mu}{\sigma^2} + \frac{T}{1 - Z\sigma^2/\mu^2} \quad (2.24)$$

Proposition 6 (Project efficiency and discount rate uncertainty) *The critical evaluation date $\bar{\tau}$ can be increasing or declining in the variance of the discount rate when it follows a gamma distribution.*

Proof. Differentiating equation (2.24) with respect to the variance of the discount rate, we see that:

$$\frac{d\bar{\tau}}{d\sigma^2} = -\frac{\mu}{(\sigma^2)^2} + \frac{Z\sigma^2/\mu^2}{\mu^2 (Z\sigma^2/\mu^2 - 1)^2} \cdot T \ln Z \quad (2.25)$$

Clearly the sign of equation 2.25 is ambiguous given that $Z > 1$. The sign depends upon the relative magnitudes of the first and second terms of equation 2.25. ■

Proposition 6 reveals once more that the characterisation of the uncertainty underlying the discount rate is important not only from the perspective of the schedule of discount rates, but also from the perspective of the critical evaluation date. However, it is interesting to ask whether or not this result is driven by the presence of a lower bound in the support of \tilde{r} . We have already seen in Chapter 1 how important this assumption was for the work of Gollier (2002a,b) and it is likely to be of considerable moment here.

2.8 Results with Negative Interest Rates

The gamma distribution proved to be a tractable way of investigating the impact of a mean-preserving spread on the critical evaluation date. However, it suffers from the problem that it rules out the possibility of negative market returns (and hence also negative discount rates). To allow for negative discount rates, we employ an extremely basic probability distribution,

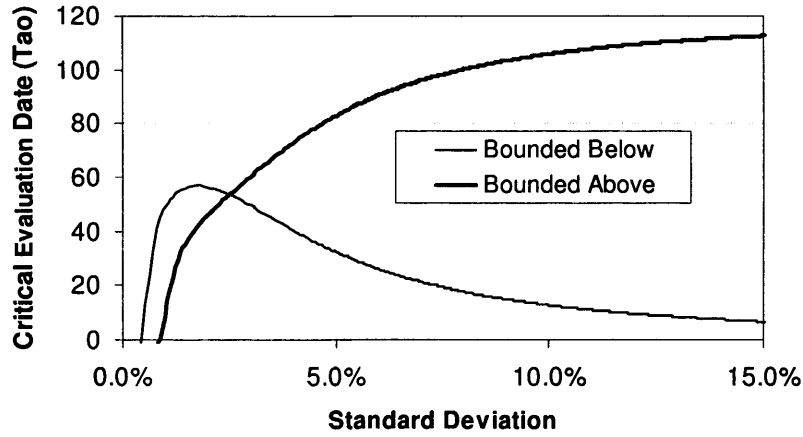


Figure 2.3: The effect of discount rate uncertainty on the critical evaluation date.

defining \tilde{r} as a lottery with realisations $\{r_{\min}, r_{\max}\}$ and corresponding probabilities $1 - p$ and p respectively. The mean discount rate is $\mu = (1 - p)r_{\min} + pr_{\max}$ and the variance is:

$$\sigma^2 = \mathbf{E}\tilde{r}^2 - \mu^2 = (1 - p)r_{\min}^2 + pr_{\max}^2 - ((1 - p)r_{\min} + pr_{\max})^2 \quad (2.26)$$

Now, taking a Gollier project and determining the critical evaluation date gives:

$$\bar{\tau} = \frac{1}{(r_{\max} - r_{\min})} \left[\log \left(\frac{(1 - p)}{p} \right) + \log (Ze^{-\tau T} - 1) - \log (1 - Ze^{-\bar{\tau} T}) \right] \quad (2.27)$$

It is possible to determine $\frac{\partial \bar{\tau}}{\partial \sigma^2}$ from this equation, and again it is of ambiguous sign — increased uncertainty can either decrease or increase the number of generations who find the sure project to be efficient¹⁴, and again this derivative depends upon the specific features of the project also. In some cases the impact of increases in the spread of the discount rate has a monotonic impact on the critical evaluation date, in other cases this is not so. Figure 2.3 illustrates two such cases.

The dependence of the critical evaluation date on the standard deviation of the discount rate is illustrated in Figure 2.3. The ‘bounded below’ function describes the case where we fix $r_{\min} > 0$ and obtain increases in σ^2 by increasing r_{\max} and adjusting probabilities to preserve the mean. It is a quasi-concave function. In contrast, the ‘bounded above’ function fixes

¹⁴If we use (2.26) and the equation for the mean for the Upper Bound case we can substitute for r_{\min} and p using $p = \frac{\sigma^2}{\sigma^2 + r_{\max}^2 - 2\mu r_{\max} + \mu^2}$ and $r_{\min} = \frac{\mu - pr_{\max}}{1 - p}$. From this we note that $\frac{dp}{d\sigma^2} > 0$ and that $\frac{dr}{dp}$ is of ambiguous sign, hence $\frac{d\bar{\tau}}{d\sigma^2}$ is of ambiguous sign. Analogous expressions exist for the Lower Bound case.

$r_{\max} > 0$ and reduces r_{\min} as the spread increases, so that eventually $r_{\min} < 0$. Note that in this instance, as the spread increases the critical evaluation date asymptotes to the time horizon, T^{15} . In the latter case, more generations prefer the safe investment since increased variance implies the possibility of ever greater negative outcomes on the risky market. In the former case ever greater positive outcomes become possible as a result of increased spread, so the overriding effect is similar to in the previous Section.

2.9 Conclusion

In a recent paper Gollier (2004a) revisited work by Weitzman (Weitzman 1998, 2001). In doing so he concludes that, under uncertainty, the prescribed schedule of the discount rates differs depending upon whether one employs an expected net present value (ENPV) or an expected net future value (ENFV) criterion in cost benefit analysis. Weitzman (1998) uses the former criterion which leads to discount rates that are declining over time. Gollier (2004a) proposes the latter criterion by way of counter-example and finds that the schedule of discount rates is *increasing* over time. Hence, he argues, these criteria are likely to yield starkly different assessments of project efficiency. Gollier also concludes that since the choice between these evaluation criteria implies imposing the investment risk upon either the present or future generations, any such decision is entirely arbitrary in the risk neutral environment in which Weitzman (1998) is cast. Gollier (2004a) summarises this apparent puzzle by saying that he and Weitzman ‘cannot both be right...and in fact...I think we are both wrong’.

The primary conclusion of this paper is that there is a clear sense in which Weitzman and Gollier *are* both right. Firstly, we show that the location of risk in time is a feature of the investment in question rather than of the chosen appraisal criterion. Thus Gollier’s explanation of the puzzle: that the choice between criteria is a question of inter-generational risk allocation, is not completely satisfactory. In fact, we show that the choice between ENPV or ENFV represents the choice across time of a specific *evaluation date*, that is, the numeraire date for CBA and as such these two criteria as presented by Gollier are special cases in a continuum of potential evaluation criteria.

Secondly, and contrary to the claim made by Gollier (2004a), we show that the schedule of

¹⁵ $\{T, Z, r_{\min}, \tau, \mu\} = \{120, 15, 0\%, 40, 2.5\%\}$ in this lower bound case, while $\{T, Z, r_{\max}, \tau, \mu\} = \{120, 15, 5\%, 40, 2.5\%\}$ in the upper bound case.

certainty-equivalent discount rates declines with the passage of time *no matter which evaluation date is employed*. It is in this sense that Weitzman is right. However, as the evaluation date is moved further into the future, the schedule of certainty-equivalent discount rates is shifted up. In short, Gollier was correct in suggesting that discount rates are increasing in one time variable, however this variable is the evaluation date, not the passage of time. So, it is in this sense that Gollier is right. In short, Weitzman's and Gollier's arguments can coexist and proponents of declining discount rates and institutions employing them — such as the UK Government — can take solace from this paper that their approach has not been invalidated by Gollier (2004a).

Thirdly, our resolution of the puzzle exposes problems of time inconsistency, that is, projects efficient from the perspective of one evaluation date may not be considered efficient at another and consequently optimal investment depends upon the evaluation date in the Weitzman framework. Hence, the main thrust of Gollier (2004a), that the choice of evaluation criteria is effectively arbitrary, still holds. Gollier (2002a, 2002b, 2004b) provides a deeper analysis, described in the previous Chapter in which the utility discount rate is assumed to remain constant, thereby avoiding problems of time inconsistency, and the importance of risk preferences in determining optimal investments is described. A third contribution of this Chapter, however, was to provide an alternative approach to the evaluation of projects by outlining a set of intergenerational efficiency rules to employed in these circumstances. Proposition 4 makes a small start at providing such guidance by demonstrating what is required for a project to be judged (1) unanimously efficient (for all generations), (2) efficient over its time horizon, (3) efficient from the perspective of the present, or (4) never efficient. Clearly, policy-makers can have complete confidence in a project that is deemed unanimously efficient by an accurate cost benefit analysis. However, insisting upon unanimous efficiency is probably too restrictive and therefore inappropriate. More appropriate perhaps is, if the current generation makes an investment for the benefit of generation τ , it is arguable that the frame of reference of the beneficiaries should be employed, and the project should be at least τ -efficient. These rules do not solve the problem of time inconsistency but they provide at least some guidance to policy makers in this area.

Finally, a caveat on these results is required. The original critique by Gollier (2004a) implicitly assumes a very high degree of *persistence* in the social discount rate. In other words, it is assumed that as soon as the investment choice is made, the discount rate uncertainty is resolved and the discount rate is constant from that moment onwards. This is obviously an

unrealistically high degree of persistence, but it serves as an approximation to more realistic econometric models, such as the random walk model of Newell and Pizer (2003) which indicate that the discount rate shows a moderate degree of persistence. Given this the approximation is perhaps not inappropriate. We employed this assumption, like Weitzman (1998, 2001) and Gollier (2004a), because any questions about empirical validity are more than compensated for by analytical tractability and economic insight. Nevertheless, given that we have shown the importance of various features of the distribution of discount rates upon the schedule of certainty equivalents and critical evaluation dates, it is worth noting that a further area of research in this area would be to reduce the assumed persistence and consider the impacts of uncertainty in an alternative model. It is to the empirical elements of this task that we turn in the following Chapter.

2.10 References

- Bernhard, Richard H 1980. 'A Simplification and an Extension of the Bernhard-deFaro Sufficient Condition for a Unique Non-Negative Internal Rate of Return'. *Journal of Financial and Quantitative Analysis*. March; 15(1): 201-09
- Gollier.C 2002a. Discounting an uncertain future. *Journal of Public Economics* 85, 149-166.
- Gollier.C 2002b. Time horizon and the discount rate. *Journal of Economic Theory* 107, 463-473.
- Gollier.C 2004a. Maximising the expected net future value as an alternative strategy to gamma discounting. *Finance Research Letters* 1, 85-89
- Gollier.C 2004b. The consumption-based determinants of the term structure of interest rates. CESInfo Working Paper 1375.
- Groom, B. Koundouri, E. Panopoulou and T. Pantelidis 2004. Model selection for estimating certainty equivalent discount rates. UCL Economics Discussion Paper 04- 02.
- Heal, G., 1998. *Valuing the Future: Economic Theory and Sustainability*, New York: Columbia University Press.
- HM Treasury, 2003. *The Green Book: Appraisal and Evaluation in Central Government*: London: HM Treasury.
- Newell, R. and Pizer, W. 2003. 'Discounting the benefits of climate change mitigation: how much do uncertain rates increase valuations?' *Journal of Environmental Economics and*

Management, Vol. 46(1), p 52-71.

Norstrom,-Carl-J (1972) 'A Sufficient Condition for a Unique Nonnegative Internal Rate of Return'. Journal of Financial and Quantitative Analysis. 7(3): 1835-39.

Pratt, J., 1964. Risk Aversion in the small and the large, Econometrica, 32, 122-136.

Strotz, R. 1956. Myopia and inconsistency in dynamic utility maximisation, Review of Economic Studies, 23, 165-180

Weitzman, M., 1998. Why the far distant future should be discounted at its lowest possible rate, Journal of Environmental Economics and Management, 36, 201-208.

Weitzman, M., 1999. 'Just keep on discounting, but...'. In P.Portney and J.Weyant (eds), Discounting and Intergenerational Equity, Washington DC, Resources for the Future, 23-30.

Weitzman, M., 2001. Gamma Discounting, American Economic Review, 91, 1, March, 261-271.

Weitzman, M.L., 2004. Statistical discounting of an uncertain distant future, mimeo, Harvard University.

2.11 Appendices

2.11.1 Appendix 1: Caveats concerning $cov(\tilde{r}, NV(\tau))$ and Proposition 4.

Proposition 4 is not true for all projects $B(t)$, but it is true for the so-called 'Gollier projects'. In particular, the assumption that $cov(r, NV(\tau)) < 0$ is certainly not true for all projects. We know that there are some projects which look more appealing with a higher discount rate and in general they are those which have costs which appear in the long term, after an initial stream of benefits. One example might be nuclear decommission. We shall call these 'liability projects' as a reference to the long-term liability.

These are projects for which the prospect exists that the internal rate of return is not unique and hence along some range of \tilde{r} , $cov(\tilde{r}, NV(\tau)) > 0$ ¹⁶. This may also apply to projects which require sequential investments: 'sequential projects', for which the relation between $NV(\tau)$ and r is not necessarily monotonic but for which the IRR is generally unique. For completeness we

¹⁶Recall the definition of the internal rate of return (IRR) as r^* :

$$r^* = \{r : NV(\tau) = 0\} \quad (2.28)$$

illustrate each of these cases.

Project 1: Gollier Project To make this concrete imagine firstly a Gollier project which for $(Z, T, \tau) = (400, 200, 0)$. $NV(\tau)$, i.e. the present value for evaluation date τ with certain discount rate r is:

$$NV(\tau) = Z \exp(-rT) - 1$$

In this case $NV(\tau)$ is monotonically declining in r as shown in Figure 2.4, with $\lim_{r \rightarrow \infty} NV(\tau)|_{\tau=0} = -1$ and $\lim_{r \rightarrow \infty} \frac{d}{dr} NV(\tau)|_{\tau=0} = 0$:

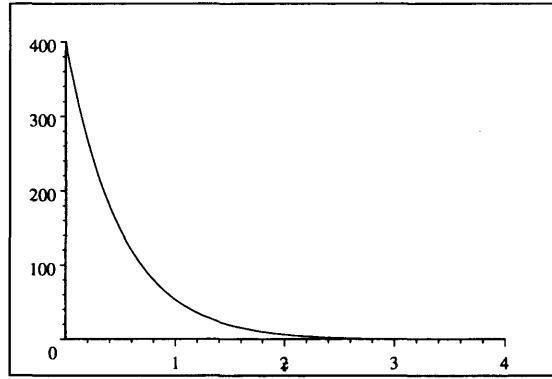


Figure 2.4: How $NV(\tau)$ varies with r in a Gollier project

Notice that the IRR is unique in this case, and approximately equal to 3%. Clearly in this case the assertion that $cov(\tilde{r}, NV(\tau)) < 0$ holds and Proposition 4 will be true. This is not dependent upon τ particularly¹⁷.

Project 2: Liability Project Now, imagine a liability project which requires a £1 at $t = 0$, yields a return of Z at time T_1 but incurs a cost of C at time $T_2 > T_1$. In this case $NV(\tau)$ defined as:

$$NPV = Z \exp(-rT_1) - C \exp(-rT_2) - 1$$

For $(T_1, T_2, \tau, Z, C) = (200, 400, 0, 400, 600)$ we have $NV(\tau)$ which varies as follows:

¹⁷We have assumed that $\tau = 0$ in the example. Imagine if $\tau > 0$, then:

$$NV(\tau) = Z \exp(-r(t - \tau)) - \exp(r\tau)$$

It is easy to see that $\lim_{r \rightarrow \infty} NV(\tau) = -\infty$. Again the decline is monotonic.

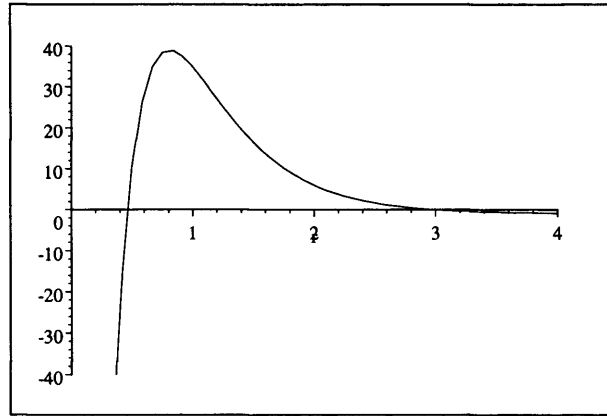


Figure 2.5: How $NV(\tau)$ varies with r for a Liability project

Given that $NV(\tau)$ is not a monotonic function of r we cannot be certain that $cov(\tilde{r}, NV(\tau)) < 0$ for projects with long-term liabilities. If we define r_{\max} as follows:

$$r_{\max} = \left\{ r : \max_{\tau} NV(\tau) \right\} \quad (2.29)$$

then in the interval $\tilde{r} \in [0, r_{\max}]$ we can see that $cov(\tilde{r}, NV(\tau)) > 0$. Furthermore, the IRR for liability projects is not unique in this case, there being 2 positive real roots. There is a low IRR, r_l , and a high IRR, r_h :

$$r_l = -\frac{1}{200} \ln \left(\frac{1}{3} + \frac{1}{60} \sqrt{394} \right) \approx 0.2\%$$

$$r_h = -\frac{1}{200} \ln \left(\frac{1}{3} - \frac{1}{60} \sqrt{394} \right) \approx 3.0\%$$

There is a broad and deeply fascinating literature specifically devoted to this point¹⁸. The issue of uniqueness hinges partly upon the number of times the accumulated net cash flow sequence, $\int B(t) dt$, changes sign over time.

Furthermore, the value of τ becomes important here. When $\tau = 0$ it is easy to see that $\lim_{r \rightarrow \infty} NV(\tau) = -1$, i.e. the initial outlay. When $\tau > 0$ however, $\lim_{r \rightarrow \infty} NV(\tau) = -\infty$. This introduces another region of $NV(\tau)$ in which $cov(\tilde{r}, NV(\tau)) < 0$. Our problems are perhaps not solved in this regard simply by looking at projects which have a unique IRR however. This can be seen by considering the following example.

¹⁸Examples include Norstrom (1972) and Bernhard (1980).

Project 3: A sequential project A sequential project is one for which two separate investments need to be made in order to reap the returns. For example it requires a £1 investment at $t = 0$, yields a return of Z at time T_1 but incurs a cost of C at time $T_2 < T_1$. In this case $NV(\tau)$ defined as:

$$NPV = Z \exp(-rT_1) - C \exp(-rT_2) - 1$$

For $(T_1, T_2, \tau, Z, C) = (200, 100, 0, 400, 200)$ we have $NV(\tau)$ which varies as follows:

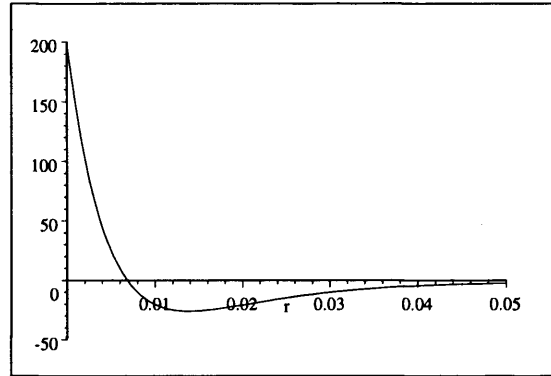


Figure 2.6: How $NV(\tau)$ varies with r for a Sequential Project

In this case the IRR is unique, but there is still a portion of the function $NV(\tau)$ which is rising with r .

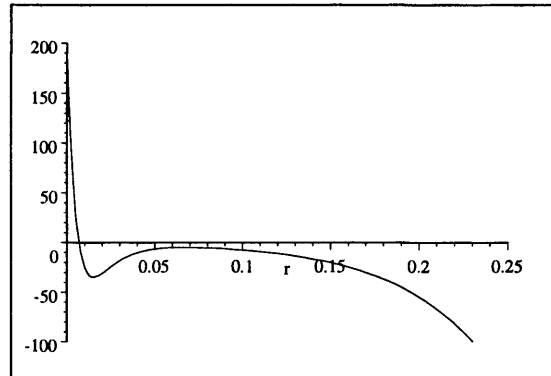


Figure 2.7: $NV(\tau)$ when $\tau > 0$.

Ultimately, however, $cov(r, NV(\tau))$ may still be negative even if there is a region of $NV(\tau, r)$ in which it is increasing in r . It is in this sense that Proposition 2 is applicable more generally

than simply to Gollier projects.

Chapter 3

Characterising uncertainty in the discount rate: Does model selection affect the certainty equivalent discount rate?

Abstract¹

In the previous chapters we have been introduced to the various arguments for declining discount rates and the practical problems that emerge in employing DDRs in CBA. Chapter 1 introduced the importance of persistence in the discount rate in the results of Weitzman (1998) and Newell and Pizer (2003). Chapter 2 saw a resolution of one of the puzzles that has arisen from those arguments for DDRs based on uncertainty of the discount rate itself. In addition to introducing some simple ideas for decision making in the face of the time inconsistency associated with DDRs we also described how the discount function, the assessment of projects and critical evaluation dates, are affected in important ways by the features of the probability distribution of the discount rate.

In this chapter we discuss in more depth the characterisation of the uncertainty surrounding the discount rate and build upon an interpretation of uncertainty found in a recent paper by Newell and Pizer (2003) (N&P). They build upon Weitzman (1998, 2001) and show how uncertainty about future interest rates leads to ‘certainty equivalent’ forward rates (CER) that decline with the time horizon. Here we discuss the determination of the empirical schedule of discount rates for use in CBA using time series econometrics. We discuss the implications of model selection for the schedule and the policy implications by reference to two case studies in the long term policy arena: climate change and nuclear build.

¹This paper is an extended version of a Department of Economics Discussion Paper number 04/02 entitled ‘Model Selection for the Certainty Equivalent Discount Rate’ by Ben Groom, Phoebe Koundouri of the University of Reading, and Ekaterini Panopoulou and Teo Pantelidis of the University of Piraeus, Greece.

3.1 Introduction

The dramatic effects of conventional exponential discounting on present values of costs and benefits that accrue in the distant future along with the issues of intergenerational equity that arise are well documented (see e.g. Portney and Weyant 1999, Pearce *et. al.* 2003). The emergence of a long-term policy arena containing issues as diverse as climate change, nuclear build and decommission, biodiversity conservation, groundwater pollution, and the use of social Cost Benefit Analysis (CBA) to guide decision-makers in this arena has brought the discussion of long-run discounting to the fore. Discount rates that decline with the time horizon (Declining Discount Rates or DDRs) have often been touted as an appropriate resolution to what Pigou (1932) described as the ‘defective telescopic faculty’ of conventional discounting, and there has been much discussion about the moral and theoretical justification for such a strategy (see e.g. Dybvig *et al.* 1996, Sozou 1998, Portney and Weyant 1999, Weitzman 1998, 2001, Gollier 2002a). Of particular interest are the declining yet socially efficient discount rates resulting from the analysis of Weitzman (1998, 2004) and Gollier (2002a,b, 2004) both of which appear to offer a theoretical path through the ‘dark jungles of the second best’ (Baumol 1968) and the intergenerational equity-efficiency trade-off contained therein.

If these theoretical solutions offer even a partial resolution of the problems of conventional discounting then it is clearly important that they can be operationalised and a schedule of DDRs can be determined. In the case of Gollier (2002a) and Weitzman (1998) it is uncertainty that drives DDRs, with regard to future growth of consumption and the discount rate respectively, thus the question of implementation is one of characterizing the uncertainty of these primals in some coherent way. However, of these two approaches it is Weitzman (1998) that has proven to be more amenable to implementation mainly because the informational requirements stop at the characterisation of uncertainty, and do not extend to specific attributes of future generations’ risk preferences as would be unavoidable in the case of Gollier (2002a, 2002b).²

Weitzman’s Certainty Equivalent Discount Rate (CER) is derived from the expected discount factor and is therefore a summary statistic of the distribution of the discount rate. The level and behaviour over time of this statistic is clearly dependent upon the manner in which uncertainty is characterised and the two applications that exist have taken different approaches

²Weitzman (1998) assumes risk neutral agents for exposition, but this represents a special case of his general point. For realistic scenarios, determination of DDRs a la Gollier (2002a, 2002b) requires knowledge of the 4th and 5th derivatives of utility functions, something that he admits is very far from being accomplished.

stemming from different interpretations of uncertainty. Weitzman (2001) defines uncertainty by the current lack of consensus on the appropriate discount rate for the very long term. His survey of professional economists results in a gamma probability distribution for the discount rate which leads to the so-called ‘gamma discounting’ approach, a version of which can also be seen in Sozou (1998). Apart from uncertainty his model has persistence in-built, the assumption being that each individual discounts the future at their preferred constant rate, that is each of the responses that make up the probability distribution remain constant over time.

More recently, Newell and Pizer (2003) (N&P, henceforth) suggest that while we are relatively certain about the current level of discount rates, there is considerable uncertainty in future. From this standpoint they assume that the past is informative about the future and characterise interest rate uncertainty by the parameter uncertainty typically found in any econometric model. They choose to describe the behaviour of the US long-term real interest rate with a reduced-form model. Their model is the direct analogue of the Vasicek (1977) model for the term structure of interest rates in the sense that only the mean equation is specified and the conditional variance is held constant. In this respect, the authors get a working definition of the CER based upon an econometric model and estimation of the CER schedule comes from a forecasting simulation. Weitzman (2004) goes one step further and builds a “statistical optimal growth model” by combining a neoclassical economic model of optimal growth under uncertainty with a fully integrated Bayesian statistical model of estimating, updating and predicting the outcome of this uncertainty. His model is able to produce persistent uncertainty in the interest rate and as a result DDRs stemming mainly from the uncertainty over future technological progress. From a different point of view, mainly driven by the existing finance literature on the term structure of interest rates, Gollier (2004) reaches similar conclusions. He, specifically, finds that a positively correlated growth process leads to a decreasing yield curve in the case of a prudent representative agent due to increased uncertainty for the distant future. He also links his model with second order stochastic correlation and as a result to the Cox, Ingersoll and Ross model (1985) (CIR, henceforth) of the finance literature, introducing the analogue of heteroscedasticity in his process for the interest rate. In two simulation experiments, one including discrete jumps in the growth of consumption and the other parameter uncertainty, he provides evidence of DDRs and suggests that the discount rate should be as low as 1% for periods exceeding 400 years.

The aforementioned studies bring to light some interesting issues concerning the character-

isation of the future path of interest rates. It is mainly persistence combined with uncertainty that leads to declines in discount rates over time. In the theoretical studies of Gollier and Weitzman, persistence is generated by the economy itself, while in N&P, the existence of persistence is an empirical question and it is the degree of persistence in the series that determines the rate of decline of the CER. In particular, N&P specify a simple AR(p) model of interest rate uncertainty, which limits the characterisation of uncertainty to a process in which the distribution of the permanent and temporary stochastic components is constant for all time. Such a process guarantees declining CERs, but it takes into account only the evolution of the mean of the process. As already mentioned their model is a discrete time version of the Vasicek (1977) continuous-time model in which the drift of the process is linear and mean-reverting, while the diffusion function is held constant. Since the seminal contribution of Vasicek (1977), an immense literature on the term structure of interest rates has produced interesting insights as to what drives efficient discount rates. The basic extensions mainly come from the specification of the variance of the process, namely the diffusion function. For example, CIR (1985) model the diffusion function as a linear function of the level of the interest rate, while Chan *et al.* (1992) allow the diffusion function to be any power function of the level of the interest rate. However, the aforementioned one-factor models display time-homogeneity, i.e. their parameters remain constant over time. It is reasonable to expect that the instantaneous return and volatility slowly evolve over time. In this respect, various efforts have been made to produce time-dependent models, such those of Ho and Lee (1986), Black, Derman and Toy (1990), Hull and White (1990) and Black and Karasinski (1991). These models specify both the drift and the diffusion process of the instantaneous stochastic rate via time-varying functions of the level of interest rates.

The empirical issues stemming from the environmental literature on declining discount rates along with the development of an econometric model, versatile enough to reproduce the empirical regularities typically encountered in interest rate data are the main concern of this paper and we build upon the following points. Firstly it is clear that, if we believe that the past is informative about the future, it is important to characterise the past as accurately as possible. Indeed, the selection of the econometric model is of considerable moment in operationalising a theory of DDRs that depends upon uncertainty and defines the CER in statistical terms. Each specification differs in the assumptions made concerning the time series process, hence the forecasts of the interest rate and the attributes of the resulting schedule of CER will differ

accordingly. Secondly, the prescription of CBA will differ markedly depending upon the empirical schedule of discount rates employed, particularly for projects with a long time horizon such as climate change prevention. Hence it is clear that we need some clear methodology for selecting among econometric models. This leads to our third point: selection among these models is also an empirical question. Typical misspecification testing and comparisons among various econometric models based upon their out-of-sample forecasting performance should guide model selection for the practitioner.

This chapter revisits these issues for US and UK interest rate data and shows that misspecification testing generates a natural progression away from the simple AR(p) specification towards models which account for second-order dependence and explicitly consider changes in the time series process over time. We employ, for comparison purposes, the same data set of the US interest rates as N&P and show the policy implications of interest rate uncertainty and model selection in the same policy issue, namely the value of carbon damages or sequestration. With regard to the UK we analyse the the value of carbon reductions and the implications for nuclear build taking consideration of the implications for carbon emissions that this would have.

3.2 From Theory to Practice

3.2.1 The Certainty Equivalent Discount Factor (CEDR) and Rate (CER)

Discounting future consequences in period t back to the present is typically calculated using the discount factor P_t , where $P_t = \exp(-\sum_{i=1}^t r_i)$. When r is stochastic, the expected discounted value of a dollar delivered after t years is:

$$E(P_t) = E\left(\exp(-\sum_{i=1}^t r_i)\right) \quad (3.1)$$

Following Weitzman (1998) we define (3.1) as the *certainty equivalent discount factor*, and the corresponding *certainty-equivalent forward rate* for discounting between adjacent periods at time t as equal to the rate of change of the expected discount factor:

$$\frac{E(P_t)}{E(P_{t+1})} - 1 = \tilde{r}_t \quad (3.2)$$

where \tilde{r}_t is the forward rate from period t to period $t + 1$ at time t in the future, or the

marginal discount rate.³ Gollier (2002a) shows that the certainty equivalent rate is the socially efficient discount rate in a risk neutral world – risk neutral agents are only concerned with the expected value of the discount factor rather than higher order moments – by showing that an arbitrage exists if this is not the case.⁴ In effect this represents the economic theory underlying Weitzman’s definition, however the behaviour of \tilde{r}_t over time is dependent upon the nature of the uncertainty surrounding the discount rate. Weitzman (1998) and N&P show that it is a declining function of time *provided there is sufficient persistence* in the series over time.⁵ This makes it clear that operationalising this theory is an empirical question, requiring the determination of the stochastic nature of \tilde{r}_t .

3.2.2 Parameterisation of real interest rates

N&P employed a simulation method to forecast discount rates in the distant future, which was properly designed to account for uncertainty in the future path of interest rates and was mainly based on the estimation results of two econometric models, namely an autoregressive Mean-Reverting (MR) model and a Random Walk (RW) model. They estimated the following $AR(p)$ model for r_t :

$$\begin{aligned} r_t &= \eta + e_t \\ e_t &= \sum_{i=1}^p a_i e_{t-i} + \xi_t \end{aligned} \tag{3.3}$$

where $\xi_t \sim N(0, \sigma_\xi^2)$, $\eta \sim N(\bar{\eta}, \sigma_\eta^2)$ and $\sum_{i=1}^p a_i < 1$ for the MR model, while $\sum_{i=1}^p a_i = 1$ for the RW model. The authors prove that in the case of an AR(1) model, the CER takes the following form:

$$\tilde{r}_t = \bar{\eta} - t\sigma_\eta^2 - \sigma_\xi^2 f(a, t) \tag{3.4}$$

where $\bar{\eta}$ is the unconditional mean discount rate, ρ is the autoregressive coefficient, $f(a, t) =$

³This is different to the average discount rate rate which is the rate which if applied in every period until period t would give the discount factor $E[P_t]$.

⁴Strictly, Gollier deals with the average certainty equivalent rate, however the same arguments hold as $t \rightarrow \infty$. His proof follows Dybvig *et al* (1996).

⁵Weitzman (1998) gives a proof for a general but time invariant distribution function of \tilde{r}_t . Weitzman (2001) estimates this distribution empirically as a Gamma distribution. Chapter 1 section 1.4.1 provided a numerical example of the decline of the certainty equivalent discount rate for a uniform distribution.

$\frac{1-a^2-2\log(a)a^{t+1}(1+a-a^{t+1})}{2(1-a)^3(1+a)}$ for MR and $f(a, t) = \frac{1}{12}(1 + 6t + 6t^2)$ for RW. It is straightforward to see that (3.4) is a declining function of t (See N&P for details).

This model, although simple, is successful in capturing the basic features of the underlying Data Generation Process (DGP) of the data which lead to DDRs, namely persistence and uncertainty. However, given the abundance of models already designed to capture the dynamics of the interest rate data either in discrete time or continuous time, it is hard to believe that simply modelling the mean of such a process is an adequate parameterisation of reality. As early as 1985, CIR introduced second-order dependence in the stochastic process of the interest rate by letting the conditional variance vary with the level of the interest rate.⁶ The simpler discretised diffusion model motivated by the CIR (1985) model is the GARCH (1,1) model, in which the conditional variance depends on its own lag as well as the lag of squared innovations. However, when fitting a GARCH model to interest rates, one often finds that the parameter estimates imply that the conditional variance process is not covariance-stationary. Engle *et al.* (1987, 1990), Hong (1988), Harvey (1993) and Kees *et al.* (1997) document such a behaviour mainly for the US short term interest rates. In such cases, proper statistical testing usually cannot reject the hypothesis that the conditional variance of the process follows an integrated GARCH process (IGARCH).

For these reasons, we employ the $AR(p)$ - $GARCH(l, m)$ model to account for both mean and volatility effects in the US interest rate process. Specifically our model is as follows:

$$\begin{aligned} r_t &= \eta + e_t \\ e_t &= \sum_{i=1}^p a_i e_{t-i} + \xi_t \\ \xi_t &= h_t^{1/2} z_t \\ h_t &= c + \sum_{i=1}^m \beta_i \xi_{t-i}^2 + \sum_{i=1}^l \gamma_i h_{t-i} \end{aligned} \tag{3.5}$$

where h_t is the conditional volatility of ξ_t (given all available information at time $t - 1$) and $z_t \sim IIDN(0, 1)$. In the case that $\sum_{i=1}^m \beta_i + \sum_{i=1}^l \gamma_i = 1$, we have an $AR(p)$ - $IGARCH(l, m)$ model.

Both the $AR(p)$ and $AR(p)$ - $GARCH(l, m)$ models assume that the parameters driving the stochastic process are constant over the sample period, i.e. they are time-homogenous. This is likely to be an unrealistic assumption for a period of 200 years and certainly for forecasting the CER over the long-term policy horizon in hand which, following N&P, extends for 400 years.

⁶Chan *et al.* (1992) extend the CIR model to include any power function for the diffusion function.

For example, the behaviour of interest rates is strongly affected by the economic cycles as well as shocks destabilising them, i.e. periods of economic crisis. In the US, during the period 1979 through 1982, the Federal Reserve Bank (FED) stopped its usual practice of targeting interest rates and decided to use non-borrowed reserves (NBRs) as a target instrument for monetary policy. As a result, the volatility of interest rates increased dramatically during that period. Other periods of high volatility of the US interest rates were the OPEC oil crisis (1973-1975), the October 1987 stock market crash and wars involving the US. Such turbulent periods are likely to induce persistence in volatility, which is often an artifact of the changes in the economic mechanism generating the interest rate (see Gray, 1996). Lamoureux and Lastrapes (1990) show that any structural shift in the unconditional variance is likely to lead to unreliable estimates of the GARCH parameters such that they imply too much persistence in volatility. In this sense, regime shifts are mistaken for periods of volatility clustering. Consequently, studies in the term structure literature have modelled discrete regime shifts in the spot interest rate process (Hamilton 1988, Das, 1994, Gray 1996 and Naik and Lee 1997). These models typically posit a spot interest rate process that can shift randomly between two or more regimes (for example a low-mean and a high-mean regime). The diffusion and drift functions are kept the same but the specific parameter values are different in each regime. This makes the process time-heterogeneous. Each regime incorporates a different speed of mean-reversion to a different long-run mean and a different unconditional variance. Specifically, in our study we consider the following Regime-Switching (RS) model with two states:

$$\begin{aligned} r_t &= \eta_k + e_t \\ e_t &= \sum_{i=1}^p a_i^k e_{t-i} + \xi_t \end{aligned} \tag{3.6}$$

where $\xi_t \sim IIDN(0, \sigma_k^2)$, $k = 1, 2$ for the first and second regime, respectively. At any particular point in time there is uncertainty as to which regime we are in. The probability of being in each regime at time t is specified as a Markov 1 process, i.e. it depends only on the regime at time $t - 1$. We define the probability that the process remains at the first regime as P , while the probability that the process remains at the second regime is Q . The matrix of the transition

probabilities is assumed to be constant.⁷

The parameterisation of a regime switching model allows us to define a finite number of states that the economy goes through, which consequently affect the interest rate. However, it does not allow for cases that both the level and the variance of the process slowly evolve over time. Such an evolution can be captured by models with time-dependent parameters. In the continuous time literature, various models have been proposed in an effort to capture this dependence of parameters in time. These include the models of Ho and Lee (1986), Black *et al.* (1990), Hull and White (1990) and Black and Karasinski (1991). Fan *et al.* (2003) compare various specifications of both time-dependent and time-independent models and propose a time-varying coefficient model which captures better the time-variation of short-term dynamics of the interest rate. This finding along with a similar conclusion of Ait-Sahalia (1996) who finds strong non-linearity of the drift for the US interest rate leads us to introduce a time varying parameter model. We model the interest rate as a State Space (SS) process. More in detail, we specify an $AR(1)$ process with an $AR(p)$ coefficient as follows:

$$\begin{aligned} r_t &= \eta + \alpha_t r_{t-1} + e_t \\ \alpha_t &= \sum_{i=1}^p \eta_i \alpha_{t-i} + u_t \end{aligned} \quad (3.7)$$

where e_t and u_t are serially independent, zero-mean normal disturbances such that:

$$\begin{pmatrix} e_t \\ u_t \end{pmatrix} \sim N \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_e^2 & 0 \\ 0 & \sigma_u^2 \end{bmatrix} \right). \quad (3.8)$$

This specification is able to capture non-linearities in the mean of the interest rate and accommodates changes in the conditional variance of the series under consideration. Tsay (1987) shows that the ARCH models can be regarded as special cases of Random Coefficient Autoregressive models (RCA), which are nested in the class of the $AR(1)$ model with an $AR(p)$

⁷We define the following matrix of transition probabilities:

$$\begin{aligned} \text{Prob}(R_t = 1 \mid R_{t-1} = 1) &= P \\ \text{Prob}(R_t = 2 \mid R_{t-1} = 2) &= Q \\ \text{Prob}(R_t = 2 \mid R_{t-1} = 1) &= 1 - P \\ \text{Prob}(R_t = 1 \mid R_{t-1} = 2) &= 1 - Q \end{aligned}$$

where R_t refers to the regime at time t .

coefficient. A simple RCA model allows for the conditional variance to evolve with previous observations, accommodating in this way the high volatility observed in periods of high interest rates. With the addition of an $AR(p)$ structure to the coefficient of our model, we are able to capture both the volatility dynamics and the observed non-linearity in the drift of the interest rate process. This time-varying coefficient model can be thought of as an infinite regime-switching model which encompasses all the previous models as special cases, given a specific set of assumptions.

Given the abundance of econometric models, our aim is to select the model that captures the dynamics of the data generating process in order to achieve an adequate description of the series under scrutiny. In doing this our intention is to provide the best prediction of the schedule of certainty equivalent discount rates for use in the evaluation of projects with implications in the far distant future. The complexity of the model and the restrictions it imposes should correspond to the level of uncertainty of the true data generating process. Otherwise, inference can be misleading and the forecasting performance of the model may be very poor. Common misspecification tests, such as tests for stationarity, autocorrelation, heteroscedasticity or parameter instability, will provide a benchmark to our selection procedure in conjunction with an out-of-sample forecasting exercise.

3.3 Empirical Results for the US

3.3.1 Data

We use the US data used by N&P (2003) for comparison purposes. More specifically, we use annual US market interest rates for long-term government bonds for the period 1798 to 1999. Starting in 1955, the nominal interest rates are converted to real interest rates by subtracting a ten-year moving average of the expected inflation rate of the CPI, as measured by the Livingston Survey of professional economists. For the previous years, expected inflation is assumed to equal zero and thus nominal and real interest rates coincide. The real interest rates are then converted to their continuously compounded equivalents. Finally, the estimation is based on a three-year moving average of the real interest rates series to smooth any short-term fluctuations, since we focus on the long-term behaviour of the series.⁸ Following N&P, we estimate our models based

⁸We follow these procedures for comparability with N&P despite some of these transformations being questionable. For example, converting the data by using a three year moving average may introduce serial correlation.

on the logs of the series. This logarithmic transformation precludes negative rates and makes interest rate volatility more sensitive to the level of interest rates.⁹

3.3.2 Estimation results

First of all, we test the stationarity of the US real interest rates. The results of a variety of unit-root tests are reported in Table 3.12 in Appendix 1¹⁰. These results generally favour the existence of a unit-root in the series, in line with the results of N&P. However, it is well-known that unit-root tests often lack the power to reject a false hypothesis of a unit-root for alternatives that lie in the neighbourhood of unity. Furthermore, mean shifts and non-linearities are often mistaken for unit-root behaviour (see, for example, Perron 1990 and Nelson *et al.* 2001). More importantly, it is difficult to believe that real interest rates become potentially unbounded with no economic forces at work to bring them back to some equilibrium, especially with two centuries of data. Albeit, for completeness, we estimate both a Random Walk (RW) and a Mean-Reverting (MR) model. Three lags are included in both models ($p = 3$).¹¹ Our estimates are identical to N&P and we do not discuss them extensively, for brevity. The MR model suggests convergence to a long-run mean of 3.69% at a very low speed though, as the sum of the autoregressive coefficients is as high as 0.976. Furthermore, tests for serial correlation in the residuals of the regression model suggest that mean dependence is sufficiently captured by this $AR(3)$ model. Not surprisingly though, this constant-variance model does a poor job in modelling the conditional volatility of interest rates as there is remaining autocorrelation in the squared residuals. Specifically, the Lagrange Multiplier (LM) test for autoregressive conditional heteroscedasticity (ARCH) in the residuals rejects the null hypothesis of homoscedasticity. In this respect, we estimate an $AR(3) - GARCH(1,1)$ model. In line with other empirical studies employing GARCH models to estimate the volatility of interest rates, we find that

More details about the data can be found in N&P (2003).

⁹See N&P (2003), footnote 15, pp.60 for a detailed discussion on this issue.

¹⁰We use the following unit root tests: the Augmented Dickey-Fuller test (Dickey and Fuller 1979), the Dickey-Fuller test with GLS detrending (Elliott *et al.* 1996), the Elliot-Rothenberg-Stock Point Optimal test (Elliott *et al.* 1996), the Phillips-Perron test (Phillips and Perron 1988), the KPSS test (Kwiatkowski *et al.* 1992) and the Ng-Perron test (Ng and Perron 2001).

¹¹Throughout this paper, we use the Schwarz Information Criterion (SIC) to select the lag-length of the alternative models.

Panel A: AR(3)-IGARCH(1,1) model			
Coefficient	Estimate	Std. Error	t-stat.
n	1.330	0.104	12.811
a_1	1.951	0.085	23.033
a_2	-1.322	0.156	-8.472
a_3	0.355	0.080	4.441
c	0.0001	0.00003	3.236
β_1	0.442	0.092	4.805
Panel B: Regime Switching model			
Coefficient	Estimate	Std. Error	t-stat.
n_1	1.189	0.128	9.327
a_1^1	1.589	0.078	20.36
a_2^1	-0.660	0.086	-7.630
n_2	1.714	0.238	7.206
a_1^2	1.787	0.050	35.55
a_2^2	-0.800	0.049	-16.395
σ_1^2	0.004	0.001	5.651
σ_2^2	0.000	0.000	6.070
P	0.867	0.058	14.934
Q	0.917	0.035	25.976
Panel C: State Space model			
Coefficient	Estimate	Std. Error	t-stat.
n	0.510	0.082	6.185
n_1	0.990	0.002	494.9
$\ln(\sigma_e^2)$	-9.158	1.324	-6.917
$\ln(\sigma_u^2)$	-6.730	0.144	-46.63

Table 3.1: Estimation Results for the US Models

$\beta_1 + \gamma_1 = 1.007$, implying that the unconditional variance of the process is unbounded.¹² However, statistical tests indicate that β_1 and γ_1 sum up to unity, implying that the process of the conditional variance of the interest rate follows an *integrated* GARCH process. In this respect, we estimate an $AR(3) - IGARCH(1,1)$ model. The estimation results are reported in panel A of Table 3.1. The estimates for the conditional mean remain the same in this setting, while the estimates for the conditional variance indicate that any shock is persistent in the sense that it remains important for future forecasts of all horizons.

However, as discussed above, this strong persistence in the volatility of the estimated GARCH model is an indication of a regime-switching mechanism in the generating process of the interest rate. In this mode, we estimate a two-regime model, where each regime is an

¹²Engle *et al.* (1990) report $\beta_1 + \gamma_1 = 1.0096$ for a portfolio of US securities, Kees *et al.* (1997) report $\beta_1 + \gamma_1 = 1.10$ for the one-month T-bills and Hong (1988) reports $\beta_1 + \gamma_1 = 1.073$.

AR(2) process. Panel B of Table 3.1 reports the estimates of this model. Both regimes are fairly persistent as indicated by the probabilities P and Q of the transition matrix which approach or even exceed 0.9. However, these regimes are distinct, as they display different characteristics. The first regime can be characterised as a “low-mean” regime, while the second as a “high-mean” one. The unconditional means for the two regimes are 3.28% and 5.55%, respectively. Different degrees of mean reversion are implied by the two regimes, as well. The “low-mean” regime mean-reverts quicker than the “high-mean” one as indicated by the sum of the autoregressive coefficients. The respective figures are 0.929 and 0.987, implying that our process is stationary in each regime. Moreover, the estimated transition matrix in combination with the estimated coefficients satisfy the condition for global stationarity of the process, which is a desirable property as far as modelling the real interest rate is concerned.¹³ Since such a type of model can just draw probabilistic assumptions about the state of the interest rate we are in, our estimates suggest that the probability (unconditional) of being in the “low-mean” regime is more than double the probability of being in the “high-mean” one (68% as opposed to 32%).¹⁴ As a result, the estimated duration of the regimes is 7.5 years and 12 years for the low-mean and the high-mean regime, respectively. Furthermore, the first regime is more volatile than the second as indicated by the higher variance of the error term. Specifically, the estimated variance of the “low-mean” regime is 10 times greater than the variance of the “high-mean” one. This finding along with the estimated duration of the regimes leads us to assume that these regimes incorporate a business cycle effect over this 200-year period. As a result, periods with low real interest rates correspond to periods of slow growth or high inflation inducing uncertainty to the overall economy, while periods of high real interest rates correspond to periods of high growth and consequently confidence about the future state of the economy.

This business cycle effect or, more generally, the evolution of economic fundamentals might not be abrupt, switching from one state to the other. A gradual change in the evolution of the economy and interest rates as well might be captured better with a state space model. We specifically model the interest rate process as an $AR(1)$ process with an $AR(1)$ coefficient. The parameter estimates for this model are presented in panel C of Table 3.1. The constant in our model suggests a minimum for the real interest rate, rather than a mean value, which is estimated at 1.67%. Furthermore, the autoregressive coefficient is strongly persistent.¹⁵ This

¹³See Franco and Zakoian (2001) for the stationarity conditions.

¹⁴See Figure 1 for the estimated states over time.

¹⁵Stability conditions for this process have been derived by Weiss (1985). Specifically, for a univariate $AR(1)$

finding cannot in itself suggest any degree of mean reversion for the process as a whole, since the degree of mean reversion of the process changes over time. At the end of our sample the process of the interest rate displays a relatively quick mean reversion as suggested by a value of 0.47 of the relevant coefficient.

So far, we have estimated five alternative models for the US interest rates. Among these models, the RW model is the only one that violates the second-order stationarity condition. This was the model preferred by N&P. From an economic point of view, the existence of a unit root in the generating mechanism of real interest rates makes little sense, since it is really hard to believe that real interest rates can potentially become unbounded with no economic dynamics at work to bring them back to their mean. As far as the rest of the estimated models are concerned, each model makes different assumptions about the level of uncertainty in the behaviour of real interest rates. MR is the simpler model, since it assumes constant conditional variance and constant parameters. The AR-IGARCH model allows for a higher level of uncertainty compared to MR by assuming a time-varying conditional variance (heteroscedasticity). On the other hand, the RS model and the SS model further increase the degree of uncertainty, since they both allow for time-varying coefficients. However, our RS model describes a process that vacillates between two regimes, while SS allows for the higher level of uncertainty among the estimated models, since it allows the autoregressive coefficient to change in each period. Indeed, as explained there is a sense in which the other models are nested in the SS model.

3.3.3 Certainty-equivalent discount rates and discount factors: US

The purpose of characterising the uncertainty surrounding the interest rate was to estimate the term structure of the interest rate by forecasting the path of the interest rate and calculating its certainty equivalent. In this Section we do this by using the estimated parameters from each of process with an AR(1) coefficient, i.e.

$$\begin{aligned}x_t &= \mu + \rho_t x_{t-1} + e_t, \\ \rho_t &= \phi \rho_{t-1} + v_t, \text{Var}(v_t) = q\end{aligned}$$

Weiss (1985) provides the following condition:

$$\begin{aligned}R + S^2(\infty) : &= \mu^2 + \frac{q}{1 - \phi^2} (1 + 4\mu^2 + 8\mu^2 \lim_{n \rightarrow \infty} \sum_{j=1}^{n-1} \frac{n-j}{n} \phi^j) + \\ &\frac{2q^2}{(1 - \phi^2)^2} (1 + \lim_{n \rightarrow \infty} \sum_{j=1}^{n-1} \frac{n-j}{n} \phi^{2j}) < 1\end{aligned}$$

This condition is satisfied for our process for all the sample sizes employed in this study.

the models described and we subsequently compare the results. We follow N&P and undertake a numerical simulation of 100,000 possible future discount rate paths for each model starting in 2000 and extending 400 years into the future. For each model presented and estimated in the previous Section the simulations are based on the estimates presented in Table 3.1.¹⁶ The initial value of the real interest rate is set at 4%, which as N&P argue reflects the best comparison with a constant rate. In Appendix 2, we briefly describe the simulation method for each estimated model. We then calculate the certainty-equivalent discount rate employing the discrete approximation of equation (3.2). The simulated expected discount factors and the corresponding CERs are reported in Table 3.2 and 3.3 respectively for the various models under consideration.

The first column of Table 3.2 displays the discount factors based on a constant 4% rate with the remaining columns corresponding to the rest of the estimated models. As expected, the models produce considerably different discount factors and the differences between them are evident even from the first 60 years. For example, for a 60 year horizon the SS model produces substantially higher valuations than the rest of the models (the difference is over 50 % in some cases). Overall, the higher valuations come from either the SS or the RW model. The present value of \$1 delivered after 100 years is \$0.05 and \$0.08 according to RW and SS respectively. The corresponding value for the rest of the models is about \$0.02. At the end of the period under examination, the RW model is the one that retains the higher value followed by the AR-IGARCH and the SS models.

Naturally, the differences among discount factor projections relevant to each model are reflected in the projected schedule of CERs. All the models accommodate declining interest rates mainly stemming from the persistence and uncertainty built in them. They differ, however, at the path they follow and the terminal values they attain. For example, SS and RW produce the lower rates for the first 100 years, reaching a CER of around 2% (half the initial value). During the same period, the MR and the AR-IGARCH models follow similar paths yielding a reduction of just 50 basis points (b.p.). In the case of RS, the CER increases slightly due to some overshooting during the first 40 years. Except for this overshooting, the RS model regains its quick declining path for the rest of the period reaching a rate of 0.7% after 400 years. The highest terminal rate is produced by the SS model, which projects a rate of 1.6%, followed by MR at 1.4%.

¹⁶The reader is referred to N&P (2003) for the estimates of the RW and the MR models (Table 1, page 63).

Model	4%	Mean	Random	AR	Regime	State
Year	Constant	Reverting	Walk	IGARCH	Switching	Space
1	0.96154	0.96154	0.96154	0.96154	0.96154	0.96154
20	0.45639	0.45906	0.46177	0.45876	0.45390	0.56424
40	0.20829	0.21661	0.22917	0.21250	0.19576	0.33136
60	0.09506	0.10471	0.12480	0.10062	0.08458	0.20296
80	0.04338	0.05150	0.07777	0.04894	0.03700	0.12889
100	0.01980	0.02567	0.05082	0.02455	0.01647	0.08408
150	0.00279	0.00476	0.02333	0.00529	0.00238	0.03132
200	0.00039	0.00095	0.01830	0.00178	0.00041	0.01255
250	0.00006	0.00022	0.01119	0.00104	0.00010	0.00526
300	0.00001	0.00006	0.00890	0.00086	0.00003	0.00227
350	0.00000	0.00002	0.00715	0.00080	0.00002	0.00100
400	0.00000	0.00001	0.00669	0.00078	0.00001	0.00044

Table 3.2: Certainty Equivalent Discount Factors for the US

Model	Mean	Random	AR	Regime	State
Year	Reverting	Walk	IGARCH	Switching	Space
1	4.00	4.00	4.00	4.00	4.00
20	3.91	3.85	3.96	4.22	2.79
40	3.76	3.46	3.88	4.31	2.59
60	3.65	3.08	3.74	4.26	2.38
80	3.58	2.60	3.60	4.18	2.23
100	3.51	2.17	3.42	4.09	2.10
150	3.36	1.39	2.75	3.79	1.91
200	3.16	0.94	1.62	3.31	1.79
250	2.87	0.75	0.65	2.46	1.72
300	2.43	0.56	0.23	1.83	1.67
350	1.87	0.43	0.09	0.95	1.64
400	1.41	0.34	0.04	0.70	1.61

Table 3.3: Certainty Equivalent Discount Rates for the US

Model	Mean	Random	AR	Regime	State
Criterion	Reverting	Walk	IGARCH	Switching	Space
AMSFE	2.058	2.171	2.102	2.323	1.832
AMSFE (B)	1.692	1.724	1.692	1.687	1.499
AMSFE (P)	1.725	1.746	1.720	1.683	1.426
AMSFE (QS)	0.842	0.870	0.848	0.879	0.760
AMSFE (TH)	1.769	1.797	1.765	1.738	1.550

Table 3.4: Average MSFEs for the US

In summary, the forecasts of the alternative models differ substantially. In this respect, we need to evaluate the models with respect to their predictive ability. Typical misspecification testing has shown that a constant coefficient model may not be able to fully capture the dynamics of the US interest rates over the period examined. Along this line of reasoning, we suggested two time-varying coefficient models (RS and SS), one accommodating abrupt changes and the other allowing for a gradual change over time in the generating mechanism of the interest rates. These two models seem eminently preferable to the constant coefficient models. In the following subSection, we perform an out-of-sample forecast exercise to select among the various models.

3.3.4 Model selection

Evaluating the out-of-sample forecasting performance of the models under consideration for the long run is impossible due to limitation of data, as forward rates exist for a maximum period of 30 years. However, we attempt to discriminate between these models on the grounds of their forecasting performance over a 30-year horizon using available real data. We specifically make use of annual nominal forward rates suggested by the term structure of the inflation-indexed US government bonds. Then, we calculate the commonly-used Mean Square Forecast Error (MSFE) and judge the models by this criterion. Alternatively, we calculate four modified MSFE criteria by incorporating four kernels¹⁷ which weigh observations by their relevant proximity to the present. The results are presented in Table 3.4.

Interestingly, the various specifications of the MSFE criterion unanimously rank the SS model first followed by the RS model in most of the cases. The AR-GARCH model ranks

¹⁷The Bartlett(B), the Parzen(P), the Quadratic-Spectral (QS) and the Tukey-Hanning (TK) kernels are the weighting functions used in our evaluation.

	Carbon Values	Relative to	Relative to	Relative to
Model	(\$/tc)	Constant Rate	Mean Reverting	Random Walk
Regime-Switching	5.22	-9.0%	-18.8%	-49.4%
Constant (4.0%)	5.74	—	-10.7%	-44.4%
AR-IGARCH	6.37	11.0%	-0.9%	-38.3%
Mean Reverting	6.43	12.0%	—	-37.7%
Random Walk	10.32	79.8%	60.5%	—
State Space	14.44	151.6%	124.6%	39.9%

Table 3.5: Value of Carbon Damages: US models

third followed by MR and then RW. In sum, if we select a model on the basis of its ability to characterise the past and its accuracy concerning forecasts of the future, we are inclined to accept the SS model as the best model (among the estimated models) to describe the US real interest rates. Our second best choice would be the RS model.

3.4 Policy Implications of Model Selection: US

The foregoing has established the importance of model selection in determining a schedule of declining discount rates for use in CBA. The differences that arise from alternative specifications of the time series process have been revealed and a method for selecting one model over another has been proposed. In this Section we highlight the policy implications of declining discount rates and the impact of model misspecification by considering the same case study as N&P, that is, climate change and the value of carbon sequestration. We establish the present values of the removal of 1 ton of carbon from the atmosphere, and hence the present value of the benefits of the avoidance of climate change damages for each of the specified models. To understand what follows it is important to be familiar with the profile of benefits resulting from the removal of 1 ton of carbon from the atmosphere. We use the estimates taken from the DICE model of Nordhaus and Boyer (2000) shown in Section 8.2 of chapter 1.

Table 3.5 shows the present value per ton of carbon emissions when evaluated using the schedule of discount rates associated with each of the models described in Section 3.2.2. The RS model gives the lower valuations followed by the conventional 4% discounting. Interestingly, the SS model gives the higher valuation followed by the RW model. For example, the present

value of carbon emissions reduction is over 150 % larger in the case of the SS model compared to the case of constant discounting at 4 %. On the other hand, the present value of the removal of 1 ton of carbon emissions from the atmosphere increases by only 12 % based on the MR's forecasts compared to the constant rate discounting approach.

The preceding discussion has argued that the RS and SS models are to be preferred over the others since they allow for changes in the interest rate generating process and have desirable properties. From the policy perspective we have established that both these models provide well specified representations of the interest rate series. However, the RS model provides roughly equivalent values of carbon to the constant discounting rate values (there is a 9% difference), while the SS model produces values that are up to 150% higher than those of the constant rate measuring \$14.4/tc compared to around \$5/tc under constant discounting. Comparing the performance of our models to the RW model used by N&P, we find that RW produces larger values of carbon than all models, valuing carbon reductions at \$10.32/tc, other than the SS model, which exceeds the RW model by about 40 %.

The disparity between the RS and the SS models, and the proximity of the carbon values generated by the former to those generated by conventional constant discounting represents a clear signal of the policy relevance of model selection in determining the CER. It is crucial from a policy perspective to make a clear judgment as to which of the two models is most appropriate to the case in hand. Our forecasting exercise reveals that the SS model is preferable to the RS model due to its lower MSFE for the 30-year horizon. Hence in the context of SS the carbon values are increased by 150% compared to conventional discounting and 40% compared to N&P's approach. In short, in the US context, the selection of econometric models on the basis of forecasting performance, and the preferred schedule of discount rates makes climate change prevention a more desirable investment.

Lastly, it is worth noting the importance of the profile of benefits being evaluated. There are likely to be alternative investments that would look more desirable when evaluated with the schedule of discount rates associated with models other than the SS model. Given that the RW model has the lowest long-run discount rate, this might be the case for investments with benefits which accrue solely in the very-long run. That is to say, although the SS model is the preferred model, this does not translate into uniformly higher present values for all potential projects and policies compared to other models.

3.5 Empirical Results for the UK

3.5.1 Data

To estimate the model of interest rate behavior, we compiled a series of real market interest rates over the two-century period 1800 to 2001. The nominal interest rate used is the United Kingdom 2 1/2% Consol Yield, while inflation is calculated by the annual change in the Consumer Price Index.¹⁸ Our choice of interest rate is limited by the availability of data as well as our desire for the longest time series available. Based on these nominal rates, we calculate real rates by subtracting the 10-year moving average inflation rate, so as to smooth short-term price fluctuations. However, even this technique leads to negative real rates for specific years due to mainly extreme events, such as oil crises or wars. In order to make our model invariant to these economic crises, which affect interest rates temporarily, we estimated the crisis-induced level of inflation by including a dummy in a small model for the inflation rate. The estimated extra-level of inflation is then subtracted from the inflation in the periods of crises and our series of positive real rates is obtained. We then convert these rates to their continuously compounded equivalents. We estimate our models, employed in the simulation of the interest rate, using a 3-year moving average of the real interest rate series to smooth very short-term fluctuations. Moreover, due to the fact that our models employed in the simulation of the interest rates do not rule out the possibility of persistent negative discount rates, we use the natural logarithms of the series in the estimation procedure.

3.5.2 Estimation results

A variety of unit root tests confirmed that the UK real interest rate is a stationary process (See Table 3.13 in Appendix 2). Panel A of Table 3.6 shows that the $AR(4)$ model displays relatively rapid reversion to the implied unconditional mean of 3.32%. However, Panel B shows that our estimates for the RS model indicate the presence of two distinct regimes (modelled as $AR(2)$ processes). The unconditional means of each are 2.14% and 3.70% and mean reversion is faster in the latter. The first regime has an estimated duration of 4 years, while the second one is more persistent with a duration of 15 years. Overall, the estimates of this model suggest that low interest rate periods are quickly mean-reverting, surrounded by greater uncertainty and transit more often to high interest rates periods which are more persistent and less uncertain. Turning

¹⁸Data provided by the Global Financial Data, Inc, available at <http://www.globalfindata.com>.

to our SS model in panel C, the parameter estimates suggest that the state process is highly persistent, almost a random-walk process, as indicated by the estimate of the autoregressive coefficient. The constant of our model suggests a minimum of 1.31% for the interest rate process. Due to the poor performance of the GARCH model in the US case we only use the better performing models in the UK case.

3.5.3 Certainty-equivalent discount rates and discount factors: UK

Based on the estimates presented in Table 3.6, we simulate 100,000 possible future discount rate paths for each model starting in 2002 and extending 400 years into the future.¹⁹ The expected discount factors and CERs are calculated from equations (4.14) and (3.2) and are reported in Tables 3.7 and 3.8. We also comment on the empirical distribution of interest rates.

The SS model yields the highest discount factors followed by the RS and AR(4) model. These differences are more pronounced during the first half of the forecast horizon. Only SS sustains some value in the distant future (400 years). Naturally, the corresponding certainty-equivalent discount rates reveal largely the opposite picture. The AR(4) model yields the higher rates during the first half of the sample, while the RS model yields the higher rates in the second half. The SS model gives consistently lower CERs that fluctuate in the range of 2.2% to 1.4%.

3.5.4 Model selection

For model selection we refer to a number of features of the models. Firstly, we describe the simulated distribution of discount factors. Our preferred method of model selection is the forecasting performance²⁰. We use the same techniques as described in Section 3.3.4. Specifically, we make use of the term structure of the inflation-indexed UK government bonds and use the

¹⁹The process of picking parameters and shocks is available from the authors upon request. Initial values for any lags of the real interest rate necessary for the simulation are set at 3.5 per cent, the rate used for CBA by the UK Treasury (HM Treasury 2003).

²⁰There are other comparisons available such as the coefficient of variation and the quantiles of the empirical distribution. The model with the lowest coefficient of variation (i.e. the ratio of standard deviation over mean) is SS, whereas the AR(4) model yields the highest coefficient. Alternatively, as a measure of uncertainty, we employ the 5% and 95% empirical percentiles. This measure seems to favour the RS model, which has the tightest confidence intervals, suggesting that uncertainty over the expected discount factor is considerably reduced. On the other hand, the percentiles of the SS model are relatively wide. These results are not reported here but can be found in Groom et al (2004).

Panel A: AR(4) model			
Coefficient	Estimate	Std. Error	t-stat.
n	1.201	0.177	6.777
a_1	1.054	0.058	18.165
a_2	-0.125	0.089	-1.392
a_3	-0.443	0.070	6.308
a_4	0.368	0.035	10.452
σ_ξ^2	0.064	0.005	13.733
Panel B: Regime Switching model			
Coefficient	Estimate	Std. Error	t-stat.
n_1	0.760	0.244	3.117
a_1^1	0.700	0.312	2.249
a_2^1	-0.212	0.312	-0.679
n_2	1.306	0.082	15.892
a_1^2	1.397	0.079	20.573
a_2^2	-0.530	0.058	-9.094
σ_1^2	0.219	0.047	4.694
σ_2^2	0.014	0.002	8.106
P	0.767	0.101	7.543
Q	0.933	0.033	28.617
Panel C: State Space model			
Coefficient	Estimate	Std. Error	t-stat.
n	0.266	0.044	6.091
n_1	0.991	0.002	438.82
$\ln(\sigma_e^2)$	-2.503	0.104	-24.049
$\ln(\sigma_u^2)$	-6.462	0.594	-10.884

Table 3.6: Estimation results for UK models

Model	3.5%	AR(4)	Regime	State
Year	Constant		Switching	Space
1	0.96618	0.96618	0.96618	0.96618
20	0.50257	0.48208	0.51472	0.61857
40	0.25257	0.23676	0.26746	0.40678
60	0.12693	0.11778	0.13981	0.27722
80	0.06379	0.05912	0.07354	0.19368
100	0.03206	0.02997	0.0389	0.13775
150	0.00574	0.00569	0.00813	0.06172
200	0.00103	0.00115	0.00177	0.02882
250	0.00018	0.00027	0.00041	0.01379
300	0.00003	0.00008	0.0001	0.00669
350	0.00001	0.00003	0.00003	0.00328
400	0.00000	0.00002	0.00001	0.00161

Table 3.7: Certainty Equivalent Discount Factors for the UK

Year/ Model	AR(4)	Regime	State
		Switching	Space
1	3.50	3.50	3.50
20	3.68	3.35	2.22
40	3.58	3.31	2.02
60	3.52	3.28	1.87
80	3.48	3.25	1.76
100	3.43	3.22	1.68
150	3.33	3.14	1.57
200	3.13	3.05	1.51
250	2.77	2.93	1.47
300	2.17	2.75	1.45
350	1.12	2.45	1.43
400	0.39	2.14	1.44

Table 3.8: Certainty Equivalent Discount Rates for the UK

Model	AR(4)	Regime	State
Criterion		Switching	Space
AMSF	2.330	1.486	0.195
AMSF (B)	0.875	0.527	0.135
AMSF (P)	0.562	0.332	0.132
AMSF (QS)	0.659	0.407	0.071
AMSF (TH)	0.818	0.480	0.137

Table 3.9: Average MSFEs for the UK

Mean Square Forecast Error (MSFE) as our selection criterion and again we calculate four modified MSFE criteria by incorporating four kernels²¹. The results are presented in Table 3.9. Interestingly, the various specifications of the MSFE criterion unanimously rank the SS model first followed by the RS model and then the AR(4) model. In sum, if we select the models on the basis of their ability to characterize the past and their accuracy concerning forecasts of the future we are inclined to prefer the SS model. Our second best choice would be the RS model²².

3.6 Policy Implications of Model Selection: UK

In this Section we highlight the policy implications of DDRs and model selection by looking at the long-term policy arena. Firstly we follow N&P and consider the present value of carbon sequestration: the removal of 1 ton of carbon from the atmosphere. Secondly, we look at nuclear build in the UK. The two are directly related since nuclear power can benefit from carbon credits under a system of joint implementation and carbon trading (see Pearce *et al.* 2003).

3.6.1 The value of carbon mitigation

Table 3.10 shows the present value per ton of carbon emissions for the UK with respect to the models described in Section 3.2.2. It is established that the present value of the removal of 1 ton of carbon from the atmosphere, and hence the present value of the benefits of the avoidance

²¹The Bartlett, the Parzen, the Quadratic-Spectral (QS) and the Tukey-Hanning (TK) kernels are the weighting functions used in our evaluation.

²²The weighting functions are as follows: Bartlett(B), Parzen(P), Quadratic-Spectral (QS) and Tukey-Hanning (TH).

Model	Carbon Values (£/tc)	Relative to Constant Rate
Constant (3.5%)	5.35	—
AR(4)	5.78	7.9%
Regime Switching	6.21	16.1%
State Space	16.73	212.6%

Table 3.10: Value of Carbon Damages: UK models

of climate change damages, differs widely for each of our models²³. The results suggest that the lower valuation is given by the conventional 3.5% discounting, followed by the AR(4) model. Interestingly, when employing the SS model, the present value of carbon emissions reduction is over 200% larger compared to the case of constant discounting.

3.6.2 The appraisal of investments in nuclear power

New nuclear build in the UK is still being considered as an option to ensure security of energy supply and adherence to Kyoto targets, and the Performance and Innovation Unit (Performance and Innovation Unit, 2002) recommended that the nuclear option should be kept open. Decommissioning represents a long-term implication of such investments, however the present-value of decommissioning costs is insignificant using conventional discounting. These costs are naturally sensitive to the use of declining discount rates. Following the same cost and price assumptions, and time horizons for construction, operation and decommissioning as in chapter 1 Section 1.8.3, we compare the NPV of investment in a nuclear power station using the DDRs associated with the state space and regime switching models. Furthermore, following Pearce et al (2003), we investigate the impact of carbon credits given to the nuclear industry based upon the social cost of carbon reflecting the lower intensity of carbon production possible compared to conventional energy. As we have seen above, the use of declining discount rates can improve the relative economics of nuclear generation by raising the social cost of carbon. The implications of these two countervailing effects, and the comparison to conventional constant discounting is presented in Table 3.11.

This casestudy highlights a sense in which DDRs are limited in accounting for intergenerational equity. Table 3.11 compares the NPV of investment in a nuclear power station using our

²³The same schedule of carbon damages is used here as for the US case.

(£/KW)	CAPEX	OPEX	DECOM	Rev/es	C C	NPV	Relative to 3.5%
3.5%	2173	2336	427	4062	228	-646	—
AR(4)	2167	2245	396	3904	215	-689	-6.6%
RS	2178	2401	479	4176	249	-633	8.0%
SS	2196	2973	1126	5170	547	-577	8.9%

Table 3.11: The Costs and Benefits of Nuclear Build in the UK

estimated DDRs. The appraisal shows that although the SS model has significant consequences for the present value of revenues and carbon credits, the present value of decommissioning and operating costs is also increased considerably. In this respect, the NPV of nuclear build is affected only marginally when evaluated using DDRs, and remains negative, although the SS and the RS models increase the NPV of the project by more than 8%.

So, there is a tension between benefits and costs that accrue in the far distant future and the use of DDRs raises both of these simultaneously: both carbon credits and decommissioning costs increase since to a large extent they accrue simultaneously. When appraising projects which have time profiles of costs and benefits of this nature, emphasis is perhaps better directed towards a more comprehensive understanding the trade-offs faced intra-temporally, by particular future generations, rather than the inter-temporal trade-off made by the current generation that DDRs address directly.²⁴

3.7 Conclusions

In response to the need to appraise projects over ever longer time horizons a number of theoretical discussions have arisen concerning the appropriacy of discount rates that fall with the time horizon considered. Such Declining Discount Rates (DDR) would add greater weight to the costs and benefits that accrue to future generations and thereby at least partially address the issue of inter-generational equity that so often besets the long term policy arena.

Weitzman's (Weitzman 1998) theoretical justification for DDRs depends upon uncertainty of the discount rate and therefore the operationalisation of this theory is highly dependent upon the manner in which one interprets and characterizes uncertainty. Weitzman (2001) suggested that it was the lack of consensus current about the correct discount rate to employ in the far

²⁴For more on this issue see Horowitz (2002)

distant future that was the source of uncertainty and his estimated gamma distribution provided the means of operationalising this theory and determining the declining Certainty Equivalent Rate (CER). Newell and Pizer (2003) (N&P) took an alternative view, suggesting that the future is the source of uncertainty and this interpretation lead naturally to an econometric forecasting approach to the measurement of uncertainty and the determination of the CER.

This paper builds on N&Ps approach in determining DDRs and it makes the following points concerning the model selection and the use of DDRs in general. Firstly, N&Ps approach is predicated upon the assumption that the past is informative about the future and therefore characterizing uncertainty in the past can assist us in forecasting the future and determining the path of CERs. We have argued that if one subscribes to this view it is important to characterize the past as well as possible by correctly specifying the model of the time series process. This is particularly so when dealing with lengthy time horizons where the accuracy of forecasts is important. Indeed the selection of the econometric model is of considerable moment in operationalising a theory of DDRs that depends upon uncertainty, because econometric models contain different assumptions concerning the probability distribution of the object of interest and hence their characterisation of the underlying economy. We have shown for US and UK interest rate data that the econometric specification should allow the data generating process to change over time, and that State Space and Regime Switching models are likely to be appropriate. Secondly, selection between well specified models can and should be undertaken by reference to measures of efficiency such as coefficients of variation, confidence bounds and out-of-sample forecast MSEs.

Our estimations, simulations and case studies bear out this assertion. The path of the CER differs considerably from one model to another and therefore each places a different weight upon the future. The policy implications of these estimates is revealed in the estimation of the value of carbon emissions reduction, with values which are up to 200% higher than when using constant discount rates in the UK, and up to 40% higher than the Random Walk model employed by N&P in the US.

The assessment of UK nuclear power reveals the limitations of DDRs in accounting for inter-generational equity. The fact that decommissioning costs and the benefits of carbon emissions reductions (for which we assume nuclear power receives credits) both accrue in the distant future means that the use of DDRs does not change the policy prescription: both values are increased by DDRs and the net present value remains negative. This example highlights the importance

of the question of valuing static/intra generational as well as intertemporal/intergenerational costs and benefits.

3.8 References

Ait-Sahalia, Y. (1996). Testing Continuous-time Models of the Spot Interest Rate. *Review of Financial Studies* 9, 385-426.

Baumol, W.J. (1968). On the Social Rate of Discount. *American Economic Review* 57, 788-802.

Black, F., E. Derman and W. Toy (1990). A One-factor Model of Interest Rates and its Application to Treasury Bond Options. *Financial Analysts Journal*, 33- 39.

Black, F. and P. Karasinski (1991). Bond and Option Pricing when Short Rates are Log-normal. *Financial Analysts Journal*, 52-59.

Chan, K.C., G.A. Karolyi, F.A. Longstaff and A.B. Sanders (1992). An Empirical Comparison of Alternative Models of the Short-term Interest Rate. *Journal of Finance* 47, 1209-1227.

Cox, J.C., J.E. Ingersoll Jr. and S.A. Ross (1985). A Theory of the Term Structure of Interest Rates. *Econometrica* 53, 385-407.

Das, S.R. (1994). Mean Rate Shifts and Alternative Models of the Interest Rate. Theory and Evidence. *Working Paper, New York University*.

Dickey, D.A. and W.A. Fuller. (1979). Distribution of the Estimators for Autoregressive Time Series with a Unit Root. *Journal of the American Statistical Association* 74, 427-431.

Dybvig, P.H., J.E. Ingersoll Jr. and S.A. Ross (1996). Long Forward and Zero-Coupon Rates Can Never Fall. *Journal of Business* 69, 1-24.

Elliott, G., T.J. Rothenberg and J H. Stock (1996). Efficient Tests for an Autoregressive Unit Root. *Econometrica* 64, 813-836.

Engle, R.F., D.M. Lilien and R.P. Robins (1987). Estimating Time Varying Risk Premia in the Term Structure: The ARCH-M Model. *Econometrica* 55, 391-407.

Engle, R.F., V.K. Ng and M. Rothchild (1990). Asset Pricing with a Factor ARCH Covariance Structure: Empirical Estimates for Treasury Bills. *Journal of Econometrics* 45, 213-237.

Fan, J., J. Jiang, C. Zhang and Z. Zhou (2003). Time-dependent Diffusion Models for Term Structure Dynamics and the Stock Price Volatility. *Statistica Sinica* 13, 965-992.

Franccq, C. and Zakoian J.-M. (2001). Stationarity of Multivariate Markov-switching ARMA

Models. *Journal of Econometrics* 102 339–364.

Gollier, C. (2002a). Time Horizon and the Discount Rate. *Journal of Economic Theory* 107 (2), 463–473.

Gollier, C. (2002b). Discounting an Uncertain Future, *Journal of Public Economics* 85, 149–166.

Gollier, C. (2004). The Consumption-based Determinants of the Term Structure of Discount Rates. *Mimeo, University of Toulouse*.

Gray, F.S. (1996). Modelling the Conditional Distribution of Interest Rates as a Regime-Switching Process. *Journal of Financial Economics* 42, 27–62.

Hamilton, J.D. (1988). Rational Expectations Econometric Analysis of Changes in Regime: An Investigation of the Term Structure of Interest Rates. *Journal of Economic Dynamics and Control* 12, 385–423.

Harvey, A.C. (1993). Long Memory in Stochastic Volatility. *Mimeo, London School of Economics*.

Ho, T.S.Y. and S. B. Lee (1986). Term Structure Movements and Pricing Interest Rate Contingent Claims. *Journal of Finance* 41 1011–1029

Hong, C. H. (1988). The Integrated Generalised Autoregressive Conditional Heteroskedastic Model: The process, Estimation and Monte Carlo Experiments. *Working Paper, University of California, San Diego, CA*.

Hull, J. and A. White (1990). Pricing Interest Rate Derivative Securities. *Review of Financial Studies* 3 (4), 573–592.

Kees, G.K., F.G.J.A. Nissen, P.C. Schotman and C.C.P. Wolff (1997). The Dynamics of Short-Term Interest Rate Volatility Reconsidered. *European Finance Review* 1, 105–130.

Kwiatkowski, D., P.C.B. Phillips, P. Schmidt and Y. Shin (1992). Testing the Null Hypothesis of Stationarity against the Alternative of a Unit Root: How Sure are we that Economic Time Series have a Unit Root? *Journal of Econometrics* 54, 159–178.

Lamoureux, G. and W. Lastrapes (1990). Persistence in Variance, Structural Change, and the GARCH Model. *Journal of Business and Economic Statistics* 23, 225–234.

Naik, V. and M. H. Lee (1997). Yield Curve Dynamics with Discrete Shifts in Economic Regimes Faculty of Commerce, University of British Columbia Working Paper.

Nelson, C.R, J. Piger and E. Zivot (2001). Markov Regime Switching and Unit-Root Tests. *Journal of Business and Economic Statistics* 19 (4), 404–415.

- Newell, R. and W. Pizer.(2003). Discounting the Benefits of Climate Change Mitigation: How Much do Uncertain Rates Increase Valuations? *Journal of Environmental Economics and Management* 46 (1), 52-71.
- Ng, S. and P. Perron (2001). Lag Length Selection and the Construction of Unit Root Tests with Good size and Power. *Econometrica* 69 (6), 1519-1554.
- Nordhaus, W.D. and Boyer, J., (2000). Warming the world: Economic Models of Global Warming, MIT Press, Cambridge, MA
- Pearce, D., B. Groom, C. Hepburn and P. Koundouri (2003). Valuing the Future: Recent Advances in Social Discounting. *World Economics* 4 (2), 121-141.
- Perron, P. (1990). Testing for a Unit Root in a Time Series with a Changing Mean. *Journal of Business and Economic Statistics* 8 (2), 153-162.
- Phillips, P.C.B. and P. Perron (1988). Testing for a Unit Root in Time Series Regression. *Biometrika* 75, 335-346.
- Pigou, A. (1932). *The Economics of Welfare*, 4th edition, Mac Millan, London.
- Portney, P. and J. Weyant (eds) (1999) Discounting and Intergenerational Equity, Washington DC: Resources for the Future.
- Sozou, P.D. (1998). On Hyperbolic Discounting and Uncertain Hazard Rates. *Proceedings of the Royal Society of London Series B-Biological Sciences* 265 (1409), 2015-2020.
- Tsay, R. (1987). Conditional Heteroskedasticity Time Series Models. *Journal of the American Statistical Association* 82, 590-604.
- Vasicek, O. (1977). An Equilibrium characterisation of the Term Structure. *Journal of Financial Economics* 5, 177-188.
- Weiss, A. (1985). The Stability of the AR(1) Process with an AR(1) Coefficient. *Journal of Time Series Analysis* 6 (3), 181-186.
- Weitzman, M. (1998). Why the Far Distant Future Should be Discounted at its Lowest Possible Rate. *Journal of Environmental Economics and Management* 36, 201-208.
- Weitzman, M. (2001). Gamma Discounting. *American Economic Review* 91 (1), 261-271.
- Weitzman, M. (2004). Discounting a Distant Future whose Technology is Unknown. *Mimeo, Harvard University*.

3.9 Appendices: Unit Root Tests and Simulation Method

3.9.1 Appendix 1: Unit root tests

The following 2 Tables show the result of the various unit root tests undertaken for the UK and the US data^{25,26,27}

Test	Lags /Bandwidth	t-stat.	5% critical value	Decision
ADF	13	-2.314	-2.877	non-stationary
Phillips-Perron	12	-2.016	-2.876	non-stationary
DF-GLS	13	-0.473	-1.942	stationary
ERS Point-Optimal	12	19.733	3.170	non-stationary
Ng-Perron	12	-0.824	-8.100	non-stationary
KPSS	15	1.158	0.463	non-stationary

Table 3.12: Unit Root Tests for US Interest Rates

TEST	Lags /Bandwidth	t-Stat.	5% crit. value	Decision
ADF	3	-3.189	-2.876	stationary
Phillips-Perron	20	-4.070	-2.876	stationary
DF-GLS	3	-3.186	-1.942	stationary
ERS Point-Optimal	20	0.965	3.164	stationary
Ng-Perron	20	-27.945	-8.100	stationary
KPSS	13	0.0421	0.463	stationary

Table 3.13: Unit Root Tests for UK interest rates

3.9.2 Appendix 2: Simulations

AR(p) Model: Regarding our first model ($AR(p)$ model), we use the normal distribution to draw random values for the coefficients of (3.3) taking into account the estimated variance-

²⁵SIC is employed to determine the lag-length of the series. The kernel sum-of-covariances estimator with Parzen weights is used, while the bandwidth is determined based on the Newey-West bandwidth selection method.

²⁶We use SIC to determine the number of lags of the dependent variable in the test specification.

²⁷The kernel sum-of covariances estimator with Parzen weights is used. The bandwidth is selected by using the Newey-West bandwidth selection method.

covariance matrix of the coefficients. Another draw from a normal distribution is employed for the estimated variance.

AR(p)- GARCH (l,m): The simulation methodology is similar to the AR(p) model, except from the fact that the multivariate normal distribution is used to generate random draws for the coefficient values of the GARCH model.

Regime Switching: The RS model offers the most computationally intensive simulation and is conducted as follows. First, we generate random values for the probabilities P and Q from a $Beta(k, j)$ distribution. The values of the parameters k and j of the Beta distribution are properly chosen in order to correspond to a Beta distribution with mean and standard deviation equal to the ones estimated. Specifically, for the US case the parameters k and j are equal to 28.8 and 4.42 for P , respectively. The corresponding values for Q are 55.17 and 5, respectively. Using the values of P and Q , we calculate the probability of being in each regime for each of the future 400 years, namely P_t and Q_t . A univariate normal distribution is used to get random draws for σ_1^2 and σ_2^2 separately according to the estimates presented in Tables C.1 and C.2 for the US and UK case respectively. Similarly to our previous simulations, the random values for the coefficient estimates, n_1 , n_2 , a_1^1 , a_2^1 , a_1^2 and a_2^2 are drawn from a multivariate normal distribution. Then, we simulate the future interest rate path 100.000 times on the grounds of the probabilities P_t and Q_t and the random draws of the coefficients.

State Space: The simulation design for the SS model is straightforward as we randomly draw the coefficient values from univariate normal distributions according to the estimated values.

Part II

Biodiversity and Deforestation: The Impacts of International Agreements and National Policies

Chapter 4

North-South bargaining in joint production: The biodiversity bargaining problem

Abstract¹

The need for a global cooperative solution to the problem of biodiversity conservation has long been understood. International institutions, in particular those of Trade-Related Intellectual Property Rights (TRIPS) and the Biodiversity Convention (CBD), have since been created with a view to allowing the potential gains from the production and international exchange of biotechnological inputs and outputs to be realized. Contrary to the intended effects, the rate of degradation of biodiverse habitats in the South has – by most estimates – not decreased. Explanations for this observation range from government failure to speculation and corruption. This paper pursues a different angle. Employing the tool of cooperative bargaining theory, it examines whether it is perhaps the very institutions designed to stimulate conservation that actually create incentives for biodiverse lands to be degraded. Building on Nash's idea of 'rational threats', we demonstrate that rather than removing the strategic incentives in the game of surplus division, current arrangements may in fact generate such incentives. This leads to two prescriptive results with a view to reconsidering the current institutional regime.

¹This chapter is joint work with Timo Goschl of the University of Heidelberg, Rupert Gatti of the University of Cambridge and Tim Swanson at University College London.

4.1 Background

The issue of north-south (developed-developing countries) interaction and interdependence has received attention from a number of strands of the economic literature. The contributions from the trade, environmental economics and growth literature have generally focused the extent to which differences in endowments, institutions and other features of the economy that reflect the different stages of development, generate particular impacts on regional income distribution, natural resources and ultimately welfare and development. Interdependence with regard to trade, Research and Development (R&D) and willingness to pay for natural resources, for example, have been analysed in the context of institutions such as trade agreements, intellectual property rights (IPR) and international environmental agreements (IEA). Furthermore, due to the relative richness of biodiversity in the tropical and sub-tropical south, coupled with the relative richness of human capital in the north, much attention has been paid to north-south interdependence in the biotech sector, the value of biodiversity in biotechnological R&D and associated institutions: IPRs, genetic resource rights, property rights for traditional knowledge and farmers rights. Many of these contributions have highlighted the potential for fruitful north-south cooperation to collapse into conflict due to local, regional or global externalities arising from the presence of public and/or informational goods, or disagreement over the distribution of gains. It is the role of international institutions in facilitating north-south cooperation that is the subject of this Chapter and by way of background, and in order to place this contribution in the literature, this section provides a brief summary of the most important and relevant contributions.

4.1.1 North-south cooperation and conflict

4.1.1.1 IPRs and trade

A seminal contribution by Krugman (1979) looks at trade and endogenous growth and contrasts the north and the south in terms of their ability to grow through innovation. The north is characterised as endowed with the capacity to innovate while the south is able only to imitate. From a global perspective both innovation and imitation are beneficial in this model, the latter facilitating technology transfer. However, once these capacities are separated into autonomous regions the potential for conflict arises because incentives are no longer aligned: the south could improve its own welfare if it were able to increase the rate of technology transfer, perhaps

through lax enforcement of IPRs, and the north could counter the loss of intellectual property with pre-emptive protectionist properties. That is, north-south conflict can ensue. Indeed, lax enforcement is a common theoretical finding of subsequent literature (Deardorff 1992, Helpman 1993, Lai and Qiu 2003). Similar punishment strategies have been noted in this context by Taylor (1993)². Indeed, many models of strategic trade and endogenous growth have looked at the impact of IPRs and concerned themselves with modelling the extent and welfare impact of technology transfers (commonly from the north to the south) involving heterogeneous trading partners and IPRs as strategic trade instruments (Grossman and Helpman, 1991, Chin and Grossman 1990)³. The possibility of a negative overall welfare effect of enforceable global patent protection is demonstrated by Deardorff (1992), who shows that the welfare losses incurred by the south outweigh the gains made by the north. These findings are partially refuted in Žigić (1998) who takes the intensity of deliberate technological spillovers as an indicator of the strength of IPR protection, and shows that mutual benefits may result from strong IPR protection. Furthermore, in a game with asymmetric information regarding the imitation capabilities of the south, Vishwasrao (1994) shows that rather than exporting its technology and incurring the risk of unintentional technological transfer, the innovating north may choose the costlier option of licensing a subsidiary in the foreign country, resulting in zero technology transfer. In a subsequent paper he finds that the form of licensing contract and distribution of gains from licensing affects the incentives of the south to protect patents (Vishwasrao 1997).

Above all however, one thing is clear in each of these settings: there are social benefits to be made provided the north and south can cooperate in joint production, use the resources that distinguish the regions to best effect and find an acceptable division of the gains. Lai and Qiu (2003) formalise this point in this context and conclude that both regions can gain from a cooperative agreement on the harmonisation of IPR regimes and liberalisation of northern goods markets.

²In Taylor's (1993) duopoly model with no entry, the Southern firm benefits from less stringent domestic protection of international patent rights if the imitation of the Northern technology is possible. While this unintentional technology transfer increases global competition and the productivity of resources employed in the South, the North is shown to react with defensive policies, leading to an overall pareto inferior outcome.

³Chin and Grossman (1991) show that the degree to which the North is able to capture the rents from its technological innovations within a north-south trading framework is determined by the extent to which the south implements the IPR regime.

4.1.1.2 Environment and trade

Of course, another way in which the south differs from the north is with regard to its endowments, particularly environmental resources. The presence of environmental rather than informational externalities is also a potential source of conflict between north and south. To a great extent global environmental problems such as climate change and biological diversity loss are rooted in such conflict. A common characterisation in this context is of a 'natural resource rich' south (biodiversity, e.g. plant genetic diversity, carbon store e.g. rainforest) and a 'environmental value rich' north. In the absence of a mechanism to transfer these values the south will enact policies or strategies that enhance private welfare and yet generate global externalities. For example, Chichilnisky (1994) shows that once again property rights can be the source of such conflict. In this case lax enforcement of resource rights in the south can motivate trade with the north and improve southern welfare and yet increase degradation. Indeed, the impact of trade upon environmental resources such as forests and fisheries has been the subject a number of important papers each of which has focussed on separate facets of this interaction. Brander and Taylor (1998) provide a recent reference point and show that trade liberalisation can adversely affect open access harvesting of natural resources in resource rich countries compared to autarky. More recently Smulders et al (2004) refine the characterisation of natural resources making them habitat dependent. Cast in this light, they show that Brander and Taylor's results depend critically on the dynamics of habitat such that tariffs, rather than liberalisation, could affect both welfare and environment adversely. In a similar vein, Polasky et al (2004) analyses the impact of north-south trade on land uses and biodiversity. In this case north-south heterogeneity is a key determinant of the effect of liberalisation. Where sufficient heterogeneity exists biodiversity may increase, but once more, this is dependent upon the nature of the environmental resources, in this case the degree of endemism.

4.1.1.3 Biodiversity, IPRs and strategic trade

With rising concern about the continued decline in biodiversity, the focus of recent research has been on the question of whether and how the economic value of biodiversity can contribute towards its conservation (Barbier et al, 1994, Goeschl and Swanson 2002). These questions are usually put within the context of the biotechnology and pharmaceutical industries, since the availability of genetic resources from areas of high biological diversity are crucial to the

success of the industries' R&D efforts. Since the destruction of undisturbed natural habitats and the expansion of commercial land uses are taken to be the driving force behind the loss of biodiversity (Heywood, 1995) the modelling of the interaction between the biotechnology industry and biodiversity commonly centres around the factors determining land use decisions (Goeschl and Swanson 1998, 2001, 2002; Deke 2001, Weitzman 2000, Simpson et al., 1996). In addition, the fact that the biotechnology industry is predominantly based in industrialised countries in the north, coupled with the fact that biodiversity hotspots are predominantly found in less developed countries south of the equator, means that the analysis is naturally cast in a north-south model.

In 1995 these issues were partially recognized in Article 27(3)b of the Trade-Related Intellectual Property Rights (TRIPS) Agreement of the GATT, which allows for patent protection for all life forms, including biological and genetic resources. As a result of this there has been much interest in the extent to which such a legal framework provides an adequate share of the rents from innovations to the south to ensure the provision of genetic diversity. Again the study of IPR regimes within the context of north-south trade in biological and genetic resources has focussed in part on strategic trade models. Ulph and Ulph (1996) study the effects of environmental policy on the competitive trade outcome in a world with imperfect markets. Furthermore, Droege and Soete (2001) use a three-stage game to study the effect of two IPR regimes: international patents and farmers rights, on the competitive trade positions and biological and cultural diversity protection. They find that welfare in the south is maximised if farmers' rights are implemented and IPRs are rejected. The highest pay-off for the North arises if both IPR regimes are implemented, as the South's cost advantage is partially captured by the North. The implementation of farmers' rights leads to the highest degree of biodiversity conservation, whereas international patent rights as the sole legal mechanism results in total biodiversity loss (Droege and Soete, 2001). The issue of how to specify property rights to genetic resources contained in traditional landraces remains an interesting area of research.

4.1.1.4 The value of biodiversity

The valuation of biodiversity is also an important related issue that has been the focus of another significant body of research. The value of biodiversity to private R&D firms has been modelled as a process of sequential search by individual firms in pursuit of commercial profits. In this framework the value of genetic resources reduces to the probability of winning the in-

novation race, multiplied by the patent-based profits the firm might expect to receive by virtue of such a discovery (Craft and Simpson, 2001, Simpson and Sedjo 1996, Simpson et al. 1996; Rausser and Small 2000). The potential undervaluation of biodiversity in the market is a commonly found result (Brown and Swierzbinski, 1989; Barbier and Aylward, 1996). Contrasting the private valuation of biodiversity with that of a social planner in the context of an ongoing race against pest resistance and pathogen adaptation, Goeschl and Swanson (2002) find that the patent regime is an inadequate measure to correct market failure in the valuation of biodiversity for R&D. This study uses the framework of creative destruction to represent the in-built incentive for continuing innovations that render previous innovations obsolete with the passage of time (Swanson and Goeschl, 1998, 2001; Aghion and Howitt 1992, Schumpeter 1942). In the case of Swanson and Goeschl (2002), innovations become obsolete not only as a result of new innovations but also as a result of an ongoing problem of pathogen adaptation, e.g. resistance to pharmaceuticals.

4.1.1.5 International agreements

There is a broad literature with regard to the role of International Environmental Agreements in overcoming regional and global conflicts and reaching cooperative outcomes, the economic principles of which are discussed at length in Barrett (2002). Key to understanding the determinants of the success of international agreements is the understanding of the incentives that regional or global environmental problems present to countries, whilst understanding the potential for strategy by each potential signatory and how this potential is affected by the features and rules of the agreement. The literature has asked the following questions in this regard: when are agreements self enforcing? (Barrett 1994), what is the best means of changing incentives? (Levy 1993), what should be the minimum participation level? (e.g. Carraro and Siniscalco 1993, Schelling 1978), To what extent are plausible treaties 2nd best? (Barrett 2002) and when should treaties and agreements be 'broad and shallow' rather than 'narrow but deep' (Barrett 2002a). These remain valid questions to ask in evaluating the success or otherwise of current international agreements.

The analysis undertaken in this Chapter draws from many areas of the literature described above with the objective of defining the fundamental underlying nature of north-south conflict. We couch our analysis in the biotechnology sector and develop a land use model which

captures the stylized differences between the north and south with regard to endowments of technology and environmental resources. Cooperation generates the greatest global surplus and international agreements have arisen to encourage this. In particular, we focus on two such agreements: the Convention on Biodiversity (CBD) of 1992 and the Trade Related Intellectual Property Rights agreement (TRIPS) of the GATT/WTO. The former emphasises financial and technological transfer as a means of internalising global externalities regarding national land use decisions (See Articles 16, 20 and 21 of the CBD), while emphasising the specific responsibility of the North for ensuring these transfers. The latter focusses on the role of international property rights harmonisation as a means of capturing and distributing global values. In this Chapter we scrutinise the ability of these agreements to solve the underlying bargaining game of surplus division and assess some of the strategic incentives that each solution may invoke.

4.2 Introduction

The need for global cooperation for the conservation of biological diversity has long been understood (Barrett 1994, Swanson 1996). In stylized terms, developed countries of the North attribute significant values to biodiversity that exists predominantly in tropical and sub-tropical areas of the developing South. The global nature of the benefits from biodiversity makes it clear that the North and the South must engage one another in order to ensure that external costs are considered in arriving at the land-use decisions that ultimately determine the amount of biodiversity conserved. This requires that both regions determine not only the appropriate allocation of their individual physical resources, but also that they come to an agreement on a reasonable division of the global surplus that results from their respective allocation decisions.

The need for cooperation is particularly palpable in the biotechnology sector. Research and development (R&D) in the pharmaceutical and plant breeding industries in the North generate innovations from which both regions stand to gain. However, it is countries in the South that are endowed with the biological diversity required as inputs into biotechnological R&D. Exchange of biodiversity inputs and biotechnological outputs between North and South therefore offers scope for considerable welfare improvements and each region must cooperate in combining their jointly valuable endowments in order to realize these gains.

What complicates this mutual interdependence between North and South is that due to the informational nature of the goods exchanged, market prices, and therefore simply trade, cannot

be relied upon to sufficiently coordinate the activities of the parties involved. A different set of institutions than market-based exchange is required to allow the potential gains from cooperation to be realized. In response to this challenge and the ongoing loss of biodiversity over the last decades (Leaky and Lewin 1995), countries agreed in early 1990s to create international institutions in order to capture the externalities inherent in biodiversity inputs and R&D outputs and thus to incentivize their production and international exchange. The Convention on Biological Diversity (CBD) in 1992 and the Trade-Related Intellectual Property Rights (TRIPS) agreement in the context of the World Trade Organization in 1994, both of which make explicit reference to biological and genetic diversity, represent the international institutions intended to facilitate cooperation and distribute the global surplus in the biotechnology sector⁴. The expected result of their creation is increased investment into biotechnological R&D in the North as a result of rents earned on intellectual property; and increased transfers going into conservation in the South as a result of payments under the Global Environment Facility (GEF), the financial vehicle created by the CBD. With the successful creation of these two institutions and implementation of their operation, the difficulty of cooperation appears to be solved.

One problem with the institutions thus designed is that by most estimates, the rate of degradation of biodiverse habitats in the South does not seem to have been affected by their introduction. Various explanations are possible. Much of the literature discusses why despite these new institutions, conservation efforts are lacking. The reasons fall under various headings. One is government failure, such as perverse subsidies (Margulis 2004), dysfunctional property rights (Southgate 2000), lack of complementary farmers' rights (Soete and Droege 2001), or insufficient pass-through of transfers from governments to local decision-makers in developing countries (Day-Rubinstein and Frisvold 2001). A second broad heading is land speculation in developing countries (Margulis 2004) and a third simply corruption (Smith et al. 2003). A less sophisticated explanation may be that ten years are not enough time for these institutions to truly impact on a process as complex as local land-use decisions.

The contribution of this paper is to ask a more fundamental question, namely whether it is perhaps the very institutions designed to stimulate conservation that actually create incentives for biodiverse lands to be degraded. The focal point of our analysis is therefore the precise

⁴In Section 27(b) of the TRIPS agreement explicit reference is made to intellectual property rights being extended to lifeforms and genetic material, while developing countries are encouraged to develop sui generis property rights systems for traditional knowledge and indigenous flora and fauna.

nature of the institutional response to the coordination problem inherent in global biodiversity management. In other words, our aim is to understand more about the specific solution to the biodiversity bargaining problem between North and South that gives this paper its title. To do this, we apply the tool of cooperative bargaining theory to derive propositions regarding two important aspects: The first is the determination of the bargaining frontier, from which a measure of efficiency of the institutions chosen can be derived. The second aspect is the set of feasible and individually rational strategies of the bargaining parties. A particular focus of this inquiry is whether – in a manner similar to the idea of ‘rational threats’ posited by Nash (1953) – the degradation of biodiversity is a bargaining option for the South.

We have five main results. The first is that the current institutional arrangements are an ‘extreme point contract’ that leaves the South indifferent between cooperation and non-cooperation. From this follows our second result, namely that the current institutional arrangements are not robust against the use of ‘rational threats’ by the South. In other words, continued degradation of biodiversity may very well be in the interest of the South even in the presence of conservation rewards paid through the GEF. Thirdly, even though the institutional arrangements are globally and individually welfare-improving, they are generally second best. In sum, we demonstrate that rather than removing the strategic incentives in the game of surplus division, current arrangements may induce such incentives. This leads to two prescriptive results with a view to reconsidering the current institutional regime: The first is that any institutional solution intended to avoid degradation of biodiversity requires payment for the stock of existing conservation as well as for any marginal increments. This is in marked contrast with the current policy of the GEF which enshrines an incremental cost approach. The second is that if the policy choice is – for some reason - between choosing to protect R&D outputs or R&D inputs, the South may prefer a regime that protects intellectual property rights (such as TRIPS) to an ‘extreme point’ contract of conservation rewards such as the GEF.

The paper proceeds as follows: In the following section, we introduce a stylized model of the biotechnology and land use in a North-South world and go on to describe the biodiversity bargaining problem between a ‘technology-rich’ North and a ‘gene-rich’ South in Section 4.4. The conditions for the existence of rational threats and thus ‘strategic destruction’ are established and illustrated with an example. Section 4.5 investigates the current institutional arrangements in the light of the preceding analysis with respect to their relative efficiency and bargaining strategies. Section 4.5.1 discusses the Convention on Biodiversity and Section 4.5.2

discusses intellectual property rights. We show that current institutions appear to place bargaining power initially in the North, and yet strategic destruction remains a viable strategy for the South. Section 4.6 concludes.

4.3 The Model: Biotechnology and Land Use

Here we develop a model to explore the interdependency between technological change, the distribution of gains between North and South, and land use decision making. This interdependence is placed in the context of agricultural biotechnology in which genetic resources, emanating from *in situ* biological diversity found in a ‘Reserve’ sector, is the major input into a plant breeding sector. In this sense we model biodiversity as an explicitly productive resource. The plant breeding sector undertakes research and development of new innovations in the form of high yielding varieties of seeds (HYVs). These HYVs are intermediate goods and can be used by domestic intensive agricultural sectors in the North, or purchased by the South, for final good production. In order to focus upon the essential elements of the North-South interaction in this context, and in line with previous models in this area (e.g. Krugman 1979, Helpman 1993, Droege and Soete 2001), we make a stylised distinction between North and South. The model builds upon the stylised fact that biodiversity is predominant in the South; the South is ‘gene rich’, whilst R&D is predominant in the North; the North is ‘technology rich’. For the purposes of the model it is assumed that the R&D sector exists solely in the North whilst the biological diversity exists solely in the South. It is also assumed that these stylised facts are inalterable, i.e. biodiversity loss is irreversible and technological innovation cannot occur in the South. In addition, the intensive and Reserve sectors in the South are assumed to be in competition with a ‘traditional’ agricultural sector which does not use HYVs from the North and thus is not augmented by technological innovations. The precise nature of these land-uses, North-South interaction, and the benefits of joint production is described in detail below.

4.3.1 The North

The Northern land endowment (L_N) represents land that has been formerly cleared of biological diversity and is allocated between two potential land uses: a relatively unproductive baseline agricultural sector and an intensive agricultural sector. In addition, the plant breeding sector is located in the North. The baseline and intensive sectors produce final output, whilst the plant

breeding sector engages in R&D and produces intermediate seeds.

Baseline production in the North produces final output but is not augmented by the innovations process and thereby the presence of Reserves in the South. It therefore represents a base-line technology. Final output from the baseline sector is represented by the net output function:

$$y_N^t = bl \quad (4.1)$$

where l is the land devoted to this sector and b is a net productivity parameter⁵. We take final output as the numeraire.

We represent the intensive and plant breeding sectors parsimoniously by assuming that they are vertically integrated. Thus the intensive sector in the North produces final output, y_N^i , using seeds, n . We assume a fixed 1 to 1 relationship between seed and land, hence land used in intensive production is equal to n . Innovations (HYVs) arrive with a probability which is positively affected by the stock of biodiversity, the Reserve sector, R , in the South. These innovations are embodied in the seeds and effectively cause a land augmenting productivity increase in the intensive sector. This innovation process is represented in a stylized fashion by the function, $\pi(R)$, which pre-multiplies the intensive sector production function. Thus, final intensive output captures the interdependent/joint nature of production as it is a function of HYVs from the North and Reserves in the South. Intensive production is represented by the net output function⁶:

$$y_N^i = \pi(R)n, \quad (\pi(0) = b, \pi'(R) > 0, \pi'(0) = \infty, \pi''(R) \leq 0) \quad (4.2)$$

The land constraint is $L_N = n + l$ and total output is therefore represented by:

$$y_N = \pi(R)n + b(L_N - n) \quad (4.3)$$

R&D and seed production for the intensive sector is undertaken by the plant breeding sector at a cost $c(\cdot)$, where $c(0) = 0, c'(\cdot) \geq 0, c''(\cdot) > 0$. In addition to domestic production of seed,

⁵This represents the output net of costs valued in terms of output. This represents a constant returns to scale production technology. The coefficient b can be thought of as being equal to a value $(e - d)$, where e represents the productivity of land devoted to this sector and d represents the costs. Thus, setting $b = 0$ is the same as assuming a zero profit condition for the baseline sector.

⁶Where $\pi'(\cdot)$ is the first derivative of the function and $\pi''(\cdot)$ is the second derivative with respect to its argument. This notation holds for the remainder of the paper and for other functions.

the North can also supply seed to the South (s). From Equations (4.1) and (4.2) it is clear that when $R = 0$ both the baseline and the intensive sectors are equally productive. However, when $R > 0$ the functional forms ensure that the intensive sector is preferred to the baseline sector over some range, and l is the residual use of land. Lastly, the North can make a transfer payment, T to the South which may be dependent upon the levels n and s and other variables. Given the land constraint the utility function for North represents all sectors and payments and is given by:

$$U_N = (\pi(R) - b)n - c(n + s) - T + bL_N \quad (4.4)$$

4.3.2 The South

The South is endowed with land, L_S . However, this land endowment represents unconverted ‘Reserve’ land which is rich in genetic diversity. Southern land can be maintained as Reserves with area R , or converted by either a traditional sector, t , or the intensive agricultural sector using seed imported from the North, s . The South benefits from the presence of Reserves, R , in precisely the same way as the North in that the productivity of the intensive agricultural sector is augmented by the arrival of new HYV’s from the R&D sector. The joint nature of final output from the intensive sector is represented by an analogous production function:

$$y_S = \pi(R)s \quad (4.5)$$

The cost of seed imports to the South is captured in the transfer T . The traditional sector is unaffected by technological innovation and hence its productivity is not augmented by the presence of Reserves. Traditional production incurs a cost $k(t)$: $k(0) = 0, k'(t) > 0, k''(t) > 0$. Southern utility is given by:

$$U_S = \pi(R)s + t - k(t) + T, \quad (4.6)$$

which is maximised with respect to t , s and the Southern land constraint: $L_S = R + t + s$, where R is the residual land allocation.

4.4 The Biodiversity Bargaining Problem: North-South Conflict and Cooperation

The North and South are characterised as interdependent: the South provides essential genetic materials as inputs to the North for the R&D process, whilst the North develops HYVs which outperform the domestic baseline sector and the traditional sector in the South. Both parties stand to gain from this interaction provided that they can facilitate the exchange of resources and adequately share the cooperative gains. This simple model represents to a large extent the fundamental facets of the North-South relationship in this industry. In this section we characterise the conflict point of this negotiation and the extent of the cooperative gains.

4.4.1 The conflict point: Autarky ($s = 0, T = 0$)

We define the conflict point as the outcome under Autarky. This provides the benchmark against which the solutions are measured. Autarky is characterised by two features: i) the absence of seed sales from North to South: $s = 0$ ii) the absence of transfers (T) that allow the social planner to achieve the optimal. Consequently the South fails to internalise the value of Reserves (R) and an externality exists. Under these circumstances the problems of the North and South are as follows:

THE SOUTH: The South maximises utility with respect to t .

$$\max_t U_S = t - k(t) \quad (4.7)$$

$$s.t. : L_S = t + R \text{ and } 0 \leq t \leq L_S \quad (4.8)$$

If $k'(0) \leq 1 < k'(L_S)$, the South's optimal use of land under Autarky, t^a , will be an interior solution and satisfy the first order condition:

$$1 - k'(t^a) = 0 \quad (4.9)$$

Let $R^a = L_S - t^a$ be the South's Reserves under Autarky.

THE NORTH: The North takes the behaviour of the South as given and maximises utility over its choice of n and l . The North's problem is as follows:

$$\max_n U_N = (\pi(R) - b)n - c(n) + bL_N \quad (4.10)$$

$$s.t. : 0 \leq n \leq L_N \quad (4.11)$$

If $c'(0) = 0$ and $c'(L_N) > \pi(L_S)$, the North's optimal land use, n^a , will be an interior solution satisfying the first order condition:

$$\pi(R^a) - b - c'(n^a) = 0 \quad (4.12)$$

This Autarky problem shows how the South causes a production externality on the North when choosing its land allocation in that it ignores the productive value of Reserves in the North. The greater the size of the traditional sector in the South (t^a) the lower is the marginal productivity of the North's intensive sector (n).

As either region always has the opportunity of production in isolation, the Autarky solutions will constitute the Conflict Point in any bargaining game conducted between the two, and the corresponding payoffs will be referred to as the 'Conflict payoffs' from hereon⁷. Furthermore, we will refer to the Autarky solution as being an 'interior solution' whenever $R^a, t^a, l^a, n^a > 0$ ⁸. In summary the conflict point/Autarky solution is characterised by the land allocations and payoffs (t^a, R^a, l^a, n^a) and (U_S^a, U_N^a) respectively.

4.4.2 First best (Social Planner) allocation

The social planner problem involves the maximisation of global surplus with respect to the land allocations n, s and t . The problem can be stated as follows:

$$\max_{n,s,t,D} U = U_S + U_N = \pi(R)(n + s) - bn + t - c(n + s) - k(t) + bL_N \quad (4.13)$$

$$s.t. R = L_S - s - t \text{ and } l = L_N - n$$

⁷Welfare in the South under autarky, U_S^a , is defined as $U_S^a = t^a - k(t^a)$, and welfare in the North is defined by $U_N^a = (\pi(R^a) - b)n^a - c(n^a) + bL_N$.

⁸Sufficient conditions for the existence of an interior solution to the Autarky problem are that $k'(0) < 1 < k'(L_S)$, $c'(0) = 0$ and $c'(L_N) > \pi(L_S) - b$.

$$\text{and } s, n, t, l, R \geq 0$$

Whenever $R^* > 0$, the first order necessary conditions yield⁹:

$$s^* \geq 0 : \pi(R) - \pi'(R)(s^* + n) - c'(n + s^*) \leq 0 \quad (4.14)$$

$$n^* \geq 0 : \pi(R) - b - c'(n^* + s) \leq 0 \quad (4.15)$$

$$t^* \geq 0 : 1 - \pi'(R)(n + s) - k'(t^*) \leq 0 \quad (4.16)$$

where $l^* = L_N - n^* \geq 0$.

A complete characterisation of the solution is unnecessary for our purposes, however Lemma 1 provides an analysis of the comparative statics of the optimal and Autarky solutions.

LEMMA 1: If the Autarky solution is interior, and the social planner wishes to keep Reserves ($R^* > 0$) then:

- a) intensive agricultural production will always be positive: $(n^* + s^*) > 0$;
- b) optimal traditional production in the South will be less than under Autarky: $t^* < t^a$;
- c) whenever there is intensive production in the North: $n^* > 0$, then the Reserve sector increases with global intensive agriculture. In short: $R^* > (<) R^a \iff n^* + s^* > (<) n^a$;
- d) if $b = 0$, i.e. profits are equal to zero in the baseline sector, then $s^* > 0$ only when $n^* = L_N$.

PROOF: a) From Equation (4.16) if $(n^* + s^*) = 0$ then $t^* = t^a$ and so $R^* = R^a$. Comparing Equations (4.12) and (4.15) when $R^* = R^a$, we have that $(n^* + s^*) = n^a > 0$, which is a contradiction.

b) If $t^* = 0$ then $t^* < t^a$ by assumption. If $t^* > 0$ then $1 - k'(t^*) \geq \pi'(R^*)(n^* + s^*) > 0 = 1 - k'(t^a)$, thus $t^* < t^a$ as $k''(\cdot) > 0$.

c) Comparing Equations (4.12) and (4.15), if $n^* > 0$, then $n^* + s^* > (<) n^a \iff R^* > (<) R^a$.

d) Given $b = 0$, comparing Equations (4.14) and (4.15); $n^* < L_N \implies s^* = 0$.

Lemma 1(b) shows that the optimal traditional sector in the South is smaller than under Autarky, however 1(c) shows that since the social value of reserves is derived from their value as

⁹In this case $\frac{\partial R}{\partial s} = \frac{\partial R}{\partial t} = -1$.

an input to R&D for intensive agricultural production, the overall level of Reserves will rise and fall with the size of the global intensive sector. How the socially optimal allocation compares with the Autarky state will depend upon the parameters of the model, particularly the relative productivity of the baseline sector in the North and the traditional sector in the South. A low value for b increases the likelihood that the socially optimal level of Reserves is higher than under Autarky. Lemma 1(d) shows that in the extreme case where the profits from the baseline sector are equal to zero ($b = 0$) the ambiguity is resolved and $R^* > R^a$ whenever the North's baseline sector remains active. In sum, the social planner is reluctant to have intensive agriculture in the South due to the loss of socially valuable Reserves this land conversion would entail, and where $b = 0$ the social planner would choose specialised regional functions: intensive production in the North and Reserves in the South.

Defining the optimal welfare under the social planner by:

$$U^* = U_N^* + U_S^* \quad (4.17)$$

allows us to define the extent of the social gains from cooperations, U^C , as the difference between the welfare under the social planner and that under Autarky:

$$U^C = U^* - (U_N^a + U_S^a) \quad (4.18)$$

Clearly, as the social planner is always able to select the Autarky outcome, $U^C \geq 0$. From Lemma 1, when the Autarky solution is interior $t^* < t^a$ and it follows that the inequality is strict - so there exist strictly positive gains from cooperation.

Figure 4.1 shows the Autarky and optimal outcomes. U^* is the socially optimal welfare frontier and represents different distributions of the surplus. Although the Social Planner is not concerned with the regional distribution of cooperative gains from biodiversity preservation, a system of lump sum transfers can facilitate any desired distribution. This can also be interpreted as the bargaining frontier of a fully cooperative outcome.

Each one of the points along U^* can be sustained as the Nash Equilibrium of a cooperative bargaining game¹⁰. However, as is well known, choosing among these Nash equilibria, i.e. the solution to bargaining problem, will depend upon the specifics of the bargaining process: the nature of the interaction between the two agents, the institutions that determine or officiate this

¹⁰See e.g. Example 1 below.

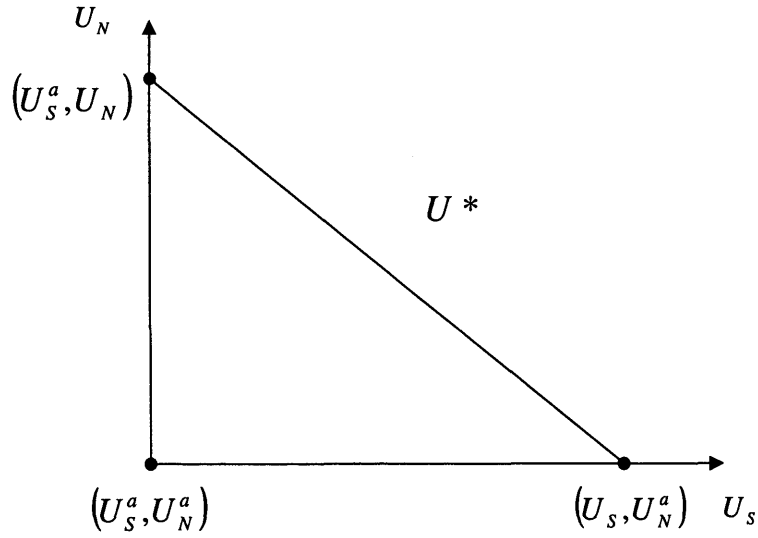


Figure 4.1: The Bargaining Frontier and Conflict Point

interaction, and the assumptions that one is willing to make concerning the behaviour of the agents. For the Biodiversity Bargaining Problem we have defined it is not easy to see how one might specify the structure of the bargaining game and therefore in moving towards a solution it is useful and informative to consider the theoretical bargaining solutions and the institutions that have actually arisen to address these issues. The following section addresses the former.

4.4.3 Bargaining solutions

4.4.3.1 Extreme point contracts

The bargaining problem can be resolved by the specification of a contract between the North and the South. Given that in the model specified there is no uncertainty or asymmetry in information between agents, an optimal contract can always be constructed to achieve any allocation of the gains from coordination between North and South. The contract actually implemented will depend upon the relative bargaining power of the two regions, that is, the biodiversity bargaining problem needs to be resolved before any optimal contract can be implemented.

Extreme point contracts specify outcomes at the end points of the bargaining frontier U^* . Such contracts are only acceptable when one or other party has absolutely no bargaining power. These types of contract are of particular interest in the present case since one of them is directly

relevant to the financial mechanism of the Convention on Biological Diversity. This relation is described in the following section. This leads to Proposition 1:

PROPOSITION 1: a) The optimal contract for the South when the North has no bargaining power is for the South to specify n^* and s^* and to offer North the transfer:

$$-T = T_S(n, s) = [\pi(R^*) - b](-n) + c(n + s) + [U_N^a - bL_N]$$

where $R^* = L_S - s^* - t^*$.

b) Inversely, the optimal contract for North when the South has no bargaining power is for the North to offer South s^* seed and the transfer:

$$T = T_N(t) = \int_t^{t^a} [1 - k'(x)] dx - \pi(L_S - s^* - t)s^*$$

PROOF: a) and b): See Appendix 1.

Proposition 1 states that if the North has no bargaining power the optimal contract offered by the South will specify (U_S, U_N^a) in terms of Figure 4.1, while inversely if the South has no bargaining power optimal contract offered by the North will specify (U_S^a, U_N) ¹¹. Each contract is optimal in the sense that it allows the agents to attain the bargaining frontier, but each merely compensates the party to whom the contract is offered for the marginal costs of changing their behaviour, leaving their welfare at Autarky levels. It is in this sense that the contracts can be thought of as ‘extreme point’ contracts, since in each case welfare for the region offered the contract is bounded only by their participation constraint $(U_i^a : i = N, S)$, i.e. the same as at the conflict point, and therefore they are indifferent between accepting or rejecting the offer. These specific contracts define the limits of the bargain.

4.4.3.2 Strategic destruction

One feature of many alternative bargaining solutions, including Nash Bargaining, is that the value received by one player (U_i^*) is not only increasing in the value of any outside option available (U_i^a) but also increasing in the maximum value of cooperation for the other player: the ‘bargaining pie’, $U^* - U_j^a$. Actions by one player which increase the value of cooperation

¹¹To see an example of this for the Nash Bargaining outcome see Example 1 and evaluate (4.19), below, and the welfare outcomes for $\alpha = 1$ and $\alpha = 0$. These represent the cases when all the bargaining power resides in the North and South respectively.

for the other player, without reducing the value of their own outside option, can be used as ‘threats’ to extract higher payoffs in a bargaining process (Nash 1953). Indeed, even where the threats are costly they may be credible depending upon the relative costs and benefits¹².

One obvious threat available to the South in this model is to destroy Reserves, making the land upon which Reserves exist (L_S) a strategic variable. In reality the destruction of Reserves can be understood either as a literal threat to destroy resources directly, as witnessed in Latin America (World Bank 2003), or as a static representation of an ongoing and irreversible process of conversion that persists in the absence of cooperation. Both interpretations imply a reduction in the land available for production: the land endowment, and the level of Reserves. Destruction of Reserves by the South is strategically viable if the value the North places on protecting the remaining Reserves increases, thus strengthening the South’s bargaining position. If the South is able to costlessly destroy land, making it incapable of supporting either Reserves or traditional production, then any Reserves remaining in Autarky can be strategically destroyed without affecting the South’s conflict payoff. The degree to which the South will want to implement strategic destruction will of course depend on the specific bargaining structure.

For example, any point of the bargaining frontier can be the solution to an asymmetric Nash Bargaining Game (NBG). It is then easy to show that strategic destruction can be a viable option for the South almost regardless of the relative bargaining power of the two parties. The solution of the NBG is a point (U_N, U_S) which maximises:

$$(U_N - U_N^a)^\alpha (U_S - U_S^a)^{(1-\alpha)} \quad \text{s.t. } U_N + U_S = U^* \quad (4.19)$$

where $\alpha \in [0, 1]$ denotes the relative bargaining strength of the North. The solution gives $U_N^* = (1 - \alpha)U_N^a + \alpha(U^* - U_S^a)$ and $U_S^* = \alpha U_S^a + (1 - \alpha)(U^* - U_N^a)$ (Nash 1953). Hence, any point on the bargaining frontier U^* can be supported depending upon the relative bargaining power.

The viability of strategic destruction in the biodiversity bargaining model can be shown as follows. Let $\overline{L_S}$ denote the maximum level of Reserves available to the South, and let $L_S = \overline{L_S} - D$ be the amount of land the South wishes to maintain, where D is the amount of land destroyed. The South will maximise returns from any asymmetric NBG by selecting $D^* = \overline{L_S} - \max[L_S^*, t^a]$ where L_S^* maximises the value of $(U^* - U_N^a)$ and has no effect upon

¹²The possibility of incentives for strategic destruction of environmental resources has also been highlighted by Copeland (1990) in the context of international fisheries management.

the South's conflict point U_S^a . Sufficient conditions for the South to credibly threaten positive levels of destruction are that $\overline{L}_S > t^a$ ($R^a > 0$) and:

$$\pi'(\overline{L}_S - t^a)(n^a) > \pi'(\overline{L}_S - s^* - t^*)(n^* + s^*) \quad (4.20)$$

PROOF: See Appendix 2.

In essence, condition (4.20) ensures that destruction increases the difference between conflict and maximum welfare obtainable for the North: the size of the 'bargaining pie', despite reducing social welfare. Example 1 illustrates this process using a Nash Bargaining solutions to the biodiversity bargaining problem modelled here.

EXAMPLE 1. Strategic destruction in a Nash Bargaining Game (NBG): If we assume the following functional forms: $\pi(R) = R^\delta$, where $\delta < 1$, $c(x) = x^\beta$, where $\beta > 1$ and $k(t) = t^\gamma$, where $\gamma > 1$. Assume that $b = 0$. Then for L_N sufficiently large, destruction is worthwhile to the South if and only if:

$$\overline{L}_S > \left(\frac{1}{\gamma}\right)^{\gamma-1} \text{ and } \beta > \frac{1}{1-\delta} \quad (4.21)$$

PROOF: See Appendix 2.

Equation (4.20) states that for destruction to increase the value of cooperation for the North, and hence be a credible threat for the South, it is sufficient that the marginal value of Reserves under the Autarky solution is higher than in the Social Planner solution. Equation (4.21) shows an explicit example of how this outcome can depend upon the relative curvature of the seed cost and R&D functions, $c(\cdot)$ and $\pi(R)$ respectively: seed costs must change more quickly than R&D productivity does in Reserves.

Example 1 and the preceding discussion reveal two important points with regard to North-South biodiversity bargaining which can be illustrated by reference to Figure 4.2. Firstly, in the process of bargaining over the rents from optimal land-uses, conditions exist in which the South can use the threat of strategic destruction to improve its payoff. It does this by increasing the value of cooperation to the North, in which its payoff is increasing, despite the fact that carrying out this threat would reduce the value of social welfare due to the loss of valuable Reserves. In terms of Figure 4.2, if the Nash Bargaining solution in the absence of threats is

carried out, i.e. U_S^D , and therefore specify a solution to the bargaining game such as point c in Figure 4.2. In effect this means that, where strategic destruction is credible i.e. if $D^* > 0$, any truly optimal contract must make two provisions; i) in order to remove the threat of destruction the South must be at least as well off as at the destruction solution, U_S^D , and hence must be compensated for the Reserves it would have kept under Autarky and; ii) compensation must be conditioned upon the *stock* of Reserves to ensure a solution on the optimal frontier. In this way a solution such as point c , in Figure 4.2 can be attained.

It should be noted that strategic destruction shifts the conflict point in such a way as to reduce the North's conflict payoff but to leave the South's unaffected. This reflects the costless nature of destruction in the South which in turn reflects the residual nature of Reserves under Autarky. In Figure 4.2 this is reflected by the conflict point moving due South from A to $A'^{15,16}$. However, the costless nature of destruction in this case does not drive the result since such threats are still credible provided the benefits outweigh the costs.

The precise nature of the bargaining solution will depend upon the particular circumstances underlying the bargaining process. In the absence of any institutional or bargaining structure in the biodiversity bargaining problem it is sufficient to define the extreme point contracts and to identify the possibility of strategic destruction as a bargaining strategy for the South under a wide variety of bargaining models. In particular it is important to recognise that the incentive for strategic destruction of Reserves exists even at the extreme points of the bargaining frontier. However, if we are willing to assume that both parties are sophisticated and fully informed, we could posit that where incentives for destruction exist, the solution to the bargaining problem would be a contract specifying a point such as point c in Figure 4.2. This point maximises global welfare and provides a more even division of rents than the suggested Nash Bargaining solution, a , and the extreme point contracts.

¹⁵In this way, the analysis here differs from other models of strategic destruction. Similar strategies have been the subject of some interest in the game theoretical literature and are relevant here. For example Ben-Porath and Dekel (1992) talk of 'burning money'. In that case the purpose of such a strategy is to determine ones preferred outcome in a coordination game with multiple equilibria. Ben-Porath and Dekel (1992) show that this can be done by destroying one's own resources or simply threatening (signalling) to do so. The difference in our case is that the South can costlessly destroy Reserves rather than engaging in self sacrifice, and the problem is one of surplus division rather than coordination.

¹⁶In Figure 2 the point bL_N represents the welfare in the North when the Reserves in the South are completely destroyed. Since we have assumed that $\pi(0) = b$, welfare in the North is equal to bL_N . This represents another limit to the bargain.

Having developed the theory in this particular case it is now apposite to investigate the impact of current institutional approaches to the biodiversity bargaining problem and how these solutions relate to theory.

4.5 Investigating the Impact of Current Institutions: Contracts and Intellectual Property Rights

There are a number of different institutions which have emerged in response to the biodiversity bargaining problem. In this section we discuss two such institutions relevant to the case in hand, one based on contracts and the other on property rights. Firstly we analyse the Convention on Biological Diversity (CBD) and the contracts implied by its financial mechanism the Global Environment Facility (GEF) ‘incremental cost’ approach. We show how this financial mechanism, which has emerged as the main coercive instrument for biodiversity conservation for signatories of the CBD, can be interpreted in light of the preceding. Secondly we model the impact of Intellectual Property Rights (IPRs), such as Plant Breeders Rights (PBRs) and patents, on this bargaining problem. In both cases we are interested in the extent to which such institutions capture the value of biodiversity and facilitate mutually beneficial joint production. Similarly, in both cases we show that current institutions appear to initially place the bargaining power in the North, and yet strategic destruction is a viable source of bargaining power for the South.

4.5.1 The CBD and strategic destruction

The CBD represents the major international institution that has emerged in response to what we have called the biodiversity bargaining problem. The CBD recognises that there are considerable gains to be made from cooperation in this regard. In short it recognises the bargaining frontier. However, article 20 of the CBD states explicitly that the implementation of commitments under the convention will depend upon the extent of financial transfers from the developed country signatories. This is implemented by means of the ‘agreed incremental cost’ concept of the Global Environment Facility (GEF) under which the North compensates the South for the costs it incurs in relation to the commitments contained in the CBD, e.g. the opportunity cost

of foregone land uses¹⁷.

Applying the incremental cost approach to the case in hand, the indicated contract is one in which the North receives the cooperative gains from innovations/intensive production and compensates the South for the welfare loss associated with the alternative use of land that occurs as the South moves away from the Autarky allocation. Thus the South ends up at its conflict payoff, represented by point (U_N, U_S^a) in Figure 4.1, which is the extreme point contract specified in Proposition 1b above. More precisely this extreme point contract very much reflects the idea of ‘net incremental’ cost: the minimum compensation required to ensure participation, which maintains the South at its pre-contract welfare level (Cervigni 1998).

Ultimately, the optimal contract between the North and South is indeterminate in the absence of some previously agreed resolution of the bargaining problem and there is no basis in principle for preferring any one over the others. The incremental cost approach merely defines one of an entire family of contracts that could facilitate the optimal outcome. The choice of an extreme point contract does not represent a complete solution to the bargaining problem for two reasons. Firstly, it implicitly assumes zero bargaining power for the South ($\alpha = 1$ in Example 1), and secondly it ignores the capacity of the South to engage in strategic bargaining, i.e. strategic destruction.

In reality bargaining power is not so unevenly allocated between regions and such bargaining strategies have been observed in practice. For example, incremental cost contracts offered by the GEF and World Bank to farmers in Latin America to encourage both changes in agricultural practices to agro-forestry and conservation of remaining forests were met with the response ‘*Bueno, corto todo*’ (OK, I’ll cut the lot!) when compensation for the existing forests was excluded from the offered contract (World Bank 2003). This brings to light the fact that dissatisfaction with the share of the surplus can lead the South not only to reject the initial contract but also to exert bargaining power in the hope of securing higher welfare upon renegotiation. The South can and does bargain with destruction as predicted by the theory outlined above. Indeed the analysis suggests that in order to eradicate the incentives for strategic destruction the optimal North-South contract should not only compensate the South for

¹⁷Cervigni (1998) discusses the extent to which the compensation should reflect the gross or net incremental costs, where net incremental cost is net of any additional benefits that the recipient country alone obtains from the presence of an unconverted or preserved environment. In this way net incremental cost is that minimum compensation required to maintain the recipient at pre-agreement welfare levels.

the incremental cost of biodiversity conservation, but compensation should also be conditioned upon the *stocks* of Reserves. This recommendation is intuitive and similar to previous work on international transfers (van Soest and Lensink 2000).

4.5.2 Bargaining under Intellectual Property Rights (IPRs)

The discussion above shows that resource ownership is an important determinant of the bargaining outcome. In the case in hand the outcome turns upon the ownership of innovations and Reserves. Therefore, it is critical to investigate the nature of property rights that currently prevail in this sector and the impact they have on the solution to the Biodiversity Bargaining problem. In this section we model what we call the Prevailing Property Rights structure (PPR) and analyse some implications for North-South bargaining.

Intellectual Property Rights (IPR) protection of innovations has long been an important institution for R&D and the focus of much investigation in the North-South context (e.g. Helpman 1993), where Plant Breeders Rights (PBRs) and patents are pertinent examples in plant breeding and biotechnology. Indeed, the potential for conflict in enforcement of IPRs across countries led to calls for international harmonisation. This culminated in the General Agreement on Trade Related aspects of Intellectual Property Rights (TRIPS) under the auspices of the World Trade Organisation (WTO)¹⁸. TRIPS specifies that any product or process innovation emanating from a signatory nation can be subject to patent protection, including plant varieties and animals. Yet, while property rights are allowed in genetic resources, most states require that they be 'improved' or 'products of human intervention' rather than simple selections or discoveries of diverse genetic resources. This allows property rights to be taken in genetic resources by those states with the human capital and technological capacity to develop natural genetic resources. It should also be recognised that in the context of the plant breeding sector the discussion about IPRs over high yielding varieties (HYVs) reflects the other side of marginal land use decisions to the CBD. That is, since modern agriculture is one of the major causes of deforestation and loss of traditional landraces (Swanson 1996), the extent to which there is transfer of HYVs to the South represents another important determinant of the extensive margin and hence the level of Reserves.

The model developed here reflects this property rights structure, that is, the PPR scenario

¹⁸The 1993 round of the GATT negotiation proposed the establishment of such an agreement, leading to the 1994 WTO TRIPS agreement.

is characterised by IPRs for innovations in the North and very little in the way of intellectual property in the South. The model allows an analysis of the impact of this property rights structure on the choice of contract by our stylised North (endowed with technology) and South (endowed with biological resources). To reflect this apparent imbalance in the strength and implementation of IPRs for innovations in biotechnology, and the absence of specific property rights for genetic traits found in South, we assume that IPRs only exist for seed innovations emanating from the North. Distinct property rights (intellectual, cultural, historical etc.) are assumed to be non-existent for the stock of information accumulated in *in situ* genetic resources supplied by the South¹⁹.

Ultimately, in the PPR model it is the North-South market for seeds that facilitates the solution to the biodiversity bargaining problem, with the solution being determined by the underlying property rights structure. The enforcement and location of IPRs gives the North some considerable advantage in determining the outcome. The PPR model places the North in the position of monopolist in the export to the South of seeds embodying technology and gives the North free access to the resources important for generating the innovations (the Reserves)²⁰. In short, discoveries of genetic information contained in Reserves are treated as a global public good. Both of these characteristics of the North reflect to a large extent the current property rights with regard to innovations and access to genetic material (Goeschl and Swanson 2002). Given this, the North is able to capture the marginal rental value of both human and fixed capital inputs to R&D (from the North) *and* the rents associated with the genetic diversity (from the South)²¹.

Characterised in this way, it seems that there are two reasons why the prevailing property rights are unlikely to be a sufficient mechanism to guarantee the supply of biodiversity from the South. Firstly, IPRs contain no provision for the South to be directly remunerated for its contribution to the R&D process. Secondly, the emergence of an intensive agricultural

¹⁹It can also be thought to tacitly represent the presence of informational spillovers which undermine the extent to which the rental value of an innovation can be uniquely attributed to a particular genetic resource in a particular country when similar traits are likely to be found in many other plant varieties in other southern countries.

²⁰The importance of the location of property rights as a means to ensure efficient incentives at each layer of a vertical industry have also been highlighted in the literature (e.g. Grossman and Hart 1986). See Goeschl and Swanson (2000, 2003a, 2003b) for a discussion relating specifically to the biotechnology industry.

²¹Evenson (1995) reminds us that plant genetic diversity had been estimated to represent up to 30% of the marginal value of innovations in the plant breeding sector.

sector in the South has the potential to lead to greater conversion of Reserve land through expansion at the extensive margin. However, there remains an important countervailing force in the PPR model: the impact of technology transfer. The North can internalise the value of biodiversity to the South through the export of seeds which embody innovations. Assuming perfect information, the South will understand that the productivity of intensive agriculture is dependent upon the presence of Reserves. Although such technology transfers can be globally suboptimal²², they cause the South to share the North's interest in biodiversity conservation (supply), and represent an important mechanism when contracting directly on Reserves is not possible²³.

This section examines the implications of the nature and location of IPRs for the resolution of the bargaining problem. The way in which the market for seeds facilitates the solution to the bargaining problem and the countervailing effects that emerge are captured in the model. The bargaining power in the North which is captured by the presence of a *first mover advantage* in a sequential model. This allows the monopolistic North to dictate the price of seeds and the extent of the technology transfer to the South, i.e. the price and quantity of seeds. By extension, the North dictates the nature of the South's land-use²⁴. In this guise, the model consists of 2 periods. In the first period the North selects the profit maximising price and quantity of exported seeds, s , and the level of domestic production, n . In the second period the South chooses its land allocations taking the price of seeds, s , as given. The model is solved by backwards induction.

4.5.2.1 Two-period model of Prevailing Property Rights (PPR)

PERIOD 1: THE NORTH. The monopolistic North faces the inverse demand curve for seeds in the South, $p(s)$ for each $s > 0$. Given this, the problem for the North is to select domestic production and export of seeds to the South, n and s , taking into account the South's choice of Reserves, \hat{R} . The North's objective becomes:

$$\begin{aligned} \max_{n,s} U_N &= (\pi(\hat{R}) - b)n + p(s)s - c(n + s) + bL_N \\ \text{s.t.} \quad &: 0 \leq n \leq L_N \end{aligned}$$

²²For example, Lemma 1 showed that where $b = 0 \implies s^* = 0$ for $0 < n^* < L_N$. Also, see Proposition 3.

²³We assume the absence of the transfers, T .

²⁴A first mover advantage for innovators is not uncommon in the literature. For theoretical approaches and empirical evidence see Petrin (2002) and Jones et al (2001).

This yields the first order conditions:

$$\hat{n} \geq 0 : \pi(\hat{R}) - b - c'(n + s) \leq 0 \quad (4.22)$$

$$\hat{s} \geq 0 : \pi'(\hat{R}) \frac{d\hat{R}}{ds} n + p(s) + sp'(s) - c'(n + s) \leq 0 \quad (4.23)$$

with at least one inequality in each case.

PERIOD 2: THE SOUTH The South takes as given the price of seeds, p , and the maximum quantity of seeds supplied by the North, \hat{s} . Given perfect information with regard to the role of Reserves in R&D, and hence the productivity of the Southern intensive sector, the South internalises the value of Reserves in making its land-use decisions. This captures what we have described above as technology transfer. Following on from the previous sections, the South's objective then becomes:

$$\max_{t,s} U_S = [\pi(L_S - t - s) - p]s + t - k(t) \quad (4.24)$$

$$s.t. : t + s \leq L_S, t \geq 0, 0 \leq s \leq \hat{s}$$

This yields the following first order conditions²⁵:

$$\hat{t} \geq 0 : 1 - \pi'(L_S - t - s)s - k'(t) \leq 0 \quad (4.25)$$

$$\bar{s} \geq 0 : \pi(L_S - t - s) - \pi'(L_S - t - s)s - p \leq 0 \quad (4.26)$$

From (4.26), we see that the inverse demand curve for seeds in the South is²⁶:

$$p(s) = \pi(L_S - t - \bar{s}) - \pi'(L_S - t - \bar{s})\bar{s} \quad (4.27)$$

Given (4.27), $\hat{t} > 0$ solves²⁷:

²⁵It is important that the second order conditions are also satisfied: $\frac{d^2 U}{dt^2} = \pi''(L_S - t - s)s - k''(t) < 0$, $\frac{d^2 U}{ds^2} = \pi''(L_S - t - s)s - 2\pi'(L_S - t - s) < 0$, $\frac{d^2 U}{dsdt} = \pi''(L_S - t - s)s - \pi'(L_S - t - s)$, and $\left(\frac{d^2 U}{dt^2}\right)\left(\frac{d^2 U}{ds^2}\right) - \left(\frac{d^2 U}{dsdt}\right)^2 > 0$.

These conditions are worked out explicitly in Appendix 3 for Example 2.

²⁶In effect this assumes that $\bar{s} = \hat{s}$.

²⁷ $\hat{t} > 0$ provided that $1 - k'(0) - \pi'(L_S - \bar{s})\bar{s} > 0$.

$$1 - \pi'(L_S - \hat{t} - \bar{s})\bar{s} - k'(\hat{t}) = 0 \quad (4.28)$$

Some comparative statics of these solutions come from total differentiation of (4.28), and show that $\frac{d\hat{t}}{d\bar{s}} < 0$ ²⁸. Hence the optimal choice of traditional production in the South is decreasing in the supply of seeds from the North. Furthermore, setting $\hat{R} = L_S - \hat{t} - \bar{s}$ yields:

$$\frac{d\hat{R}}{d\bar{s}} = -\frac{d\hat{t}}{d\bar{s}} - 1 \quad (4.29)$$

The relationship in (4.29) is of particular interest in our land use model since it characterises the net marginal effect of intensive agriculture in the South upon Reserves. For example, where (4.29) is less than zero, intensive agriculture will encroach upon Reserves. However, where (4.29) is greater than zero the North can use the transfer of technology (provision of seeds) to the South as an incentive mechanism for increasing land held as Reserves. The necessary conditions for this incentive to exist are that $\hat{t} > 0$ and $\frac{d\hat{t}}{d\bar{s}} < -1$, so in this case intensive production *and* Reserves replace the traditional sector in the South²⁹. Hence there are two possible motives for the North to transfer technology to the South. One is to obtain profits from the export of seeds and the other is to incentivise the provision of Reserves. The relative strength of these motives will determine the optimal marginal response by the South to an increase in intensive production and ultimately the net effect on Reserves as compared to the Autarky and social planner outcomes.

The 2 period PPR model represents another solution to the biodiversity bargaining problem outlined above. A number of important issues arise in the characterisation of this solution, primary among which are the relationship with the social planner solution and the incentives for strategic bargaining. Firstly, we analyse the welfare implications for each region under the PPR, then we analyse the incentives for strategic destruction that emerge in the South. The implications of the model are summarised in a series of propositions.

4.5.2.2 PPR vs Social Planner

The following proposition provides the first fundamental distinction between PPR and social planner outcomes:

²⁸Note that $\frac{d\hat{t}}{d\bar{s}} = \frac{-[\pi''(L_S - \hat{t} - \bar{s})\bar{s} - \pi'(L_S - \hat{t} - \bar{s})]}{\pi''(L_S - \hat{t} - \bar{s})\bar{s} - k''(\hat{t})} < 0$. This comes from the second order conditions.

²⁹From the previous footnote: $\pi'(L_S - \hat{t} - \bar{s}) > k''(\hat{t})$ ensures that $\frac{d\hat{t}}{d\bar{s}} < -1$.

PROPOSITION 2: When the social planner solution is interior, the PPR problem is never a solution to the social planner problem and therefore the solution falls within the bargaining frontier (U^* in Figure 4.1)³⁰. If $b = 0$, there are zero profits in the Northern baseline sector, the social planner chooses specialised functions for each region (intensive production in the North, Reserves in the South) and again the PPR and social planner solutions never coincide and the PPR solution falls within the bargaining frontier.

PROOF: Where the social planner solution is interior: $n^*, l^*, s^*, R^*, t^* > 0$, from (4.25), if $(n^*, s^*) = (\hat{n}, \hat{s})$ then if $R^* = \hat{R}$ it follows due to the convexity of $k(\cdot)$ that $t^* < \hat{t}$. If $b = 0$ then by Lemma 1 $s^* = 0$, but if $\hat{s} = 0$ the PPR solution coincides with the Autarky solution, which is not the social planner solution. QED.

It is clear from comparison of (4.25) and (4.16) that the decentralised South always imposes an externality upon the North under the PPR in determining traditional and Reserve land use, albeit smaller than under Autarky. This externality, which arises because the transfer of technology (seeds) only internalises the private value of Reserves to the South, captures the fact that the South is not being explicitly remunerated for the provision of Reserves. This effect will tend to reduce the level of Reserves below R^* . As a result, where the North is unable to contract directly over Reserves, and can only determine the price and quantity of seeds, the PPR outcome will be suboptimal and within the bargaining frontier. This situation is depicted in Figure 4.3.

This externality is but one source of inefficiency in the PPR model. Indeed a comparison of (4.23) with (4.15) shows that there exist two further distortions. Firstly there is the effect of monopolistic pricing reflected by the term $p'(s)$ in (4.23). This reflects the pure monopoly distortion. Secondly, there is a distortion introduced by the term $\frac{d\hat{R}}{ds}$, which reflects the optimal

³⁰Indeed this is generally the case. There are several other cases to consider. a) $n^* = L_N, s^* = L_S$: From the assumption that $\pi'(0) = \infty$, this is not a solution to the social planner problem (SP); b) Where $s^* = \hat{s} = 0$ then PPR solution collapses to the autarky solution which by Lemma 1 is not a solution to the SP; c) where the autarky solution is interior, $s^* = n^* = 0$ is not a solution to the SP and so the SP, autarky and PPR solutions will not all coincide in this way. The only other case to consider is where $n^* = 0$ and $s^* > 0$, i.e. the SP solution is not interior. If we assume that the PPR and SP land allocations are identical and that $n^* = 0$ and $s^* > 0$, we can set (23) and (14) equal and using the inverse demand curve $p(s)$ we can rearrange to show that the PPR solution and the SP solution coincide only if $p'(s) = 0$, i.e. if the North has no monopoly power and the price of seeds represents their (global) social value.

response of Reserves to intensive agriculture by the South. As discussed above, the sign of $\frac{d\hat{R}}{ds}$ is critical to determining the overall effect of technology transfer to the South on land allocations in the PPR model compared to the social planner and Autarky outcomes. Gatti et al (2004) discuss these effects in more detail, labelling the former effect the ‘IPR effect’ and the latter the ‘Spillover effect’, referring to the extent of knowledge spillovers. They also show that where the marginal value in R&D is relatively high, Reserves in the PPR solution are higher than under Autarky but that, given the other distortions, Reserves in the PPR regime are generally lower than optimal: $R^* > \hat{R} > R^a$. This reflects the discussion above: on the one hand intensive agriculture may encroach upon the Reserve sector, but on the other this technology transfer may internalise the value of Reserves to the South sufficiently to increase the South’s provision of Reserves compared to Autarky.

In sum these two externalities ensure that the solution to the PPR falls within the bargaining frontier. However, our main interest here is the regional welfare arising from the PPR solution. This is captured by the following proposition:

PROPOSITION 3: When the PPR solution has $\hat{s} > 0$, the South is as least as well off under the PPR solution than under either Autarky or the optimal extreme point contract offered by the North under the GEF, i.e. $\hat{U}_S \geq U_S^a$. The North is better off under the PPR regime than under Autarky: $\hat{U}_N > U_N^a$.

PROOF: The Autarky solution is available in the PPR model but is not chosen.

Proposition 3 states that, although global welfare is less than that under the social planner solution or the GEF contract described above, the PPR regime offers a more favourable solution from the perspective of the South as compared to either Autarky or the GEF contract. The North is also better off under this regime than under Autarky³¹. Figure 4.3 provides a diagrammatic representation of the PPR solution. Despite the inefficiency introduced by the North’s monopoly over innovations, and the South’s tendency to impose an externality upon the North in its land-use decision, both parties can improve their welfare compared to Autarky levels when IPRs underlie the bargaining process. The North-South market for seeds allows the South to share in the rents generated from Reserves as an input to R&D and aligns regional incentives for the conservation of Reserves such that they increase compared to Autarky. Of course, the

³¹It is ambiguous whether the North and/or the South are better off in the PPR than under the GEF with the threats of strategic destruction actually carried out.

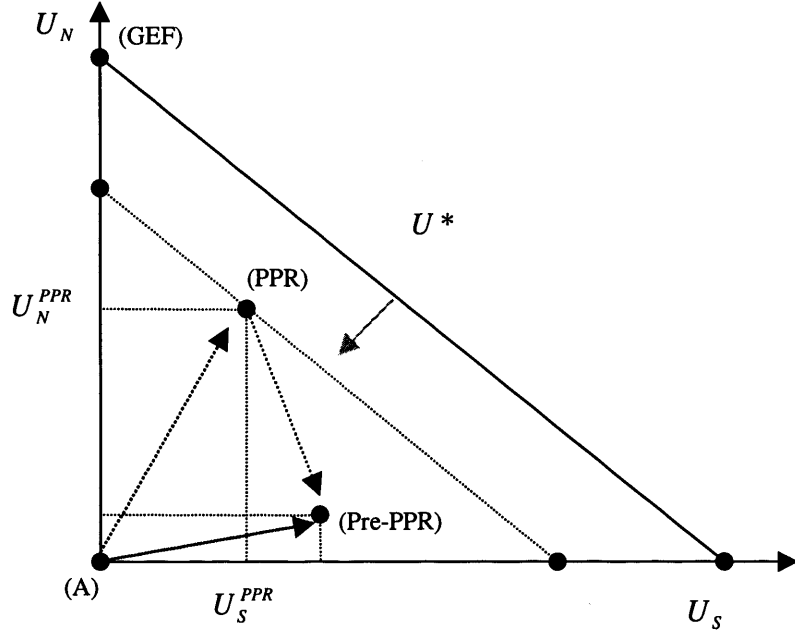


Figure 4.3: Strategic Destruction in the PPR model.

extent to which the sharing of rents aligns regional incentives depends upon the information available to the South and even then the threat of strategic destruction may persist.

4.5.2.3 Strategic destruction: Pre-PPR

In this section we follow on from Section 4.3 and investigate the extent to which incentives exist for strategic destruction. The PPR scenario differs from the pure contracts case since, given the transfer of technology in the form of seeds, destruction of Reserves is a costly activity for both the North and the South. We model the decision to engage in strategic destruction as the 'Pre-PPR' decision in which in a period 0 prior to the supply decisions of the North, the South makes a supply decision of its own: the supply of Reserves. As before, the ability of the South to make this supply decision prior to the North, reflects the only semblance of bargaining power that the South holds: the control of its land endowment and hence Reserves.

PERIOD 0: THE SOUTH CHOOSES DESTRUCTION For strategic destruction to be a credible action for the South requires welfare to increase as the land endowment decreases: $\frac{dU_S}{dL_S} < 0$. From the 2 period problem described above, and using the inverse demand

curve (4.27) U_S can be written:

$$U_S = \left(\pi(\hat{R}) - p(\hat{s}) \right) \hat{s} + \hat{t} - k(\hat{t}) = \pi'(\hat{R}) \hat{s}^2 + \hat{t} - k(\hat{t}) \quad (4.30)$$

Given $\hat{R} = L_S - \hat{s} - \hat{t}$, and the envelope theorem, we obtain:

$$\frac{dU_S}{dL_S} = 2\pi'(\hat{R}) \frac{d\hat{s}}{dL_S} \hat{s} + \pi''(\hat{R}) \left[1 - \frac{d\hat{s}}{dL_S} \right] \hat{s}^2 \quad (4.31)$$

This leads to the following proposition:

PROPOSITION 4: A sufficient condition for strategic destruction of Reserves by the South being a welfare enhancing policy is that the equilibrium level of the intensive sector in the South is increasing with destruction in the South: $\frac{d\hat{s}}{dL_S} < 0$. Indeed, $\frac{d\hat{s}}{dL_S} < 0$ is a necessary condition when $\pi''(.) = 0$. Where $\frac{d\hat{R}}{ds} > (<) 0$, this is more (less) likely where; i) $\pi''(.)$ is large in absolute value; ii) $c''(.)$ is large; and iii) n is large.

PROOF: It is easy to see from (4.31) the sufficiency of $\frac{d\hat{s}}{dL_S} < 0$ for the case where $\pi''(.) < 0$ and the necessity of $\frac{d\hat{s}}{dL_S} < 0$ when $\pi''(.) = 0$. The conditions i) - iii) under which $\frac{d\hat{s}}{dL_S} < 0$, can be derived from comparative statics analysis using equations (4.22) and (4.23) and Cramer's rule³².

The general case is complicated so we illustrate the credibility of strategic destruction with the following example in which we assume that $\pi(R)$ is linear ($\pi''(.) = 0$). This is a more restrictive case in the sense that while $\pi''(.) < 0$, the incentive for strategic destruction may exist even when $1 > \frac{d\hat{s}}{dL} > 0$. In the linear case below, $\frac{d\hat{s}}{dL_S} < 0$ is a necessary condition for strategic destruction.

EXAMPLE 2. Strategic destruction in the IPR model: We use the following algebraic form for the functions described above: $\pi(R) = \delta R$, $c(x) = \beta x^2$, $k(t) = t^2$. Some algebra yields the following expressions for the quantities and prices that determine the South's utility in the 2-period model:

$$\hat{t} = \frac{1 - \delta\hat{s}}{2}, \quad \hat{s} = \frac{\delta^2(\frac{\delta}{2} - 1)(L_S - \frac{1}{2}) + b(2\beta - \delta(\frac{\delta}{2} - 1))}{(4\delta\beta - (\delta(\frac{\delta}{2} - 1))^2)}, \quad \hat{R} = L_S - \frac{1}{2} + (\frac{\delta}{2} - 1)\hat{s} \quad (4.32)$$

and from (4.27):

³²The condition being: $\frac{ds}{dL_S} < 0 \Leftrightarrow \frac{dR}{ds} \left[\frac{\pi'(\cdot)}{c''(\cdot)} + n \frac{\pi''(\cdot)}{\pi'(\cdot)} \right] < 1$.

$$p(s) = \delta \left(L_S - \frac{1}{2} \right) + 2 \left(\frac{\delta}{4} - 1 \right) \delta \hat{s} \quad (4.33)$$

There are a number of cases to consider, however we restrict our analysis to the interior. An interior solution for t requires that $\hat{s} < \frac{1}{\delta}$, while $\frac{d\hat{p}}{ds} < 0$ if $\delta < 4$. It is only in this case that the North can employ its optimal pricing policy, $p(s)$ ³³. From Proposition 4 we have that $\frac{d\hat{s}}{dL_S} < 0$ is a sufficient condition for $\frac{dU_S}{dL_S} < 0$ in general, but a necessary condition in the linear case. The expression for \hat{s} in (4.32) above shows that the necessary condition is satisfied when $\delta < 2$ and the second order conditions. Interior solutions for the remaining variables place restrictions on the other parameters in the system. However, the result is that strategic destruction occurs under the following parameter values for example: $\delta = 1, \beta = \frac{1}{4}, b = \frac{1}{3}$ and $L_S = 1$. See Appendix 3 for a formal proof.

4.5.2.4 Discussion of the PPR model and strategic destruction

In the previous sections we have motivated a model of prevailing property rights in the biotech industry in which the North has monopoly power over the sale of seeds by virtue of the intellectual property rights over embodied innovations. Within this institution the South is modelled as having no bargaining power over the price of seed and hence the North has some discretion over the intensive land allocation in the South by virtue of being a monopolist over seeds³⁴. In the two period model the South makes residual decisions over the traditional and Reserve sector. The PPR model offers a solution to the bargaining problem described in Section 4.3 which is facilitated primarily by the market for seeds and the technology transfer that this entails. However, we have also shown that this institutional solution to the biodiversity bargaining problem may still introduce incentives for strategic destruction by the South and, importantly, the conditions under which these incentives exist are less restrictive than for the pure Nash Bargaining game outlined in Example 1. In the NBG case the productivity of Reserves ($\pi(R)$) must be concave whereas Example 2 shows that such incentives exist in the PPR even in the

³³Where $\frac{dp}{ds} > 0$ it is easy to show that $\frac{dU_S}{ds} < 0$. Note that where $\hat{s} < \frac{1}{\delta}$ the pricing formula becomes:

$p(\hat{s}) = \delta(L_S - \hat{t} - \hat{s}) - \delta\hat{s} = \delta(L_S - \frac{1}{2}) + 2(\frac{\delta}{4} - 1)\hat{s}$. Hence when $\delta > 4$, $\frac{dp}{ds} > 0$. In this case the South's utility becomes: $U_S = \frac{1}{4} + \delta\hat{s}^2(1 - \frac{\delta}{4})$, and therefore if $\delta > 4$ the South is better off with $\hat{s} = 0$, i.e. under Autarky. In other words, when $\delta > 4$ the optimal pricing policy of the North does not satisfy the South's participation constraint and hence prices must be tempered to ensure participation.

³⁴This is stark of course with the assumed fixed proportions technology, but this general point still holds without this assumption.

restrictive case where production is linear in Reserves. In short, the South has bargaining power to the extent that it can exert control over the supply of its own unique endowments in order to increase its welfare.

The PPR model brings to light some interesting points with regard to the behaviour of the North. When the North is a monopolist there are potentially two separate reasons for providing seeds to the South (see Gatti et al 2004, for more detail). On the one hand the North wishes to make profits from this transfer of technology and this is facilitated by pricing seeds according to the profit maximising pricing formula in (4.27) above. On the other hand, where $\frac{d\hat{R}}{ds} > 0$, the North can use technology transfer as a means of incentivising the South to conserve Reserve land. In general, in the former case the North will act more or less like a conventional monopolist by restricting seed sales to the South compared to the social planner. It is interesting to note that the extent to which the monopolist can exert this monopoly power is limited by the potential introduction of the traditional sector in the South, the presence of which increases the elasticity of demand for seeds³⁵. In the latter case, where technology transfer encourages the conservation of reserves, the incentives for the North to restrict seeds will be diminished since the increase in Reserves will increase R&D and benefit both their domestic intensive productivity and the price they are able to charge the South. As the power of the incentive (value of $\frac{d\hat{R}}{ds}$) increases, the Northern monopolist could end up supplying more seed than the social planner would choose. Of course, the extent to which this incentive exists is limited by the extent to which there is a traditional sector in the South to replace. Once $\hat{t} = 0$, then the intensive sector and Reserve margins meet and further intensive production necessarily encroaches on Reserves: $\frac{d\hat{R}}{ds} = -1$.

Which of these cases prevails depends upon a number of factors but hinges crucially upon the marginal value of Reserves to R&D: the higher the value the more likely it is that $\frac{d\hat{R}}{ds} > 0$. Example 2, is illustrative of this point. Where the traditional sector exists in the South ($\hat{t} > 0$), the term $\frac{d\hat{R}}{ds} = (\frac{\delta}{2} - 1)$, where δ is the marginal value of Reserves, is constant and hence the analysis is much simplified. If Reserves have a low value (< 2) then $\frac{d\hat{R}}{ds} < 0$ and the North behaves as a conventional monopolist by restricting the sale of seeds to the South.

³⁵Evaluating (25) at $\hat{t} = 0$, it is clear that the traditional sector, t , will be introduced when $1 - \pi'(R)s > 0$. Note that where $\hat{t} = 0$, $\hat{R} = L_S - s$, so as s becomes smaller the term $\pi'(R)s$ declines. Thus, restricting the seeds sold to the South will increase the likelihood that the traditional sector will be introduced. This acts as a limit to the monopoly power of the North.

Alternatively if Reserves have a moderate value ($4 > \delta > 2$) then $\frac{d\hat{R}}{ds} > 0$. In this case the sale of seeds incentivises the South to provide Reserves hence reducing the incentive for the monopolist to restrict seeds since domestic intensive production becomes more productive as seed is exported³⁶.

Under the conditions outlined in Proposition 4, strategic destruction still remains a viable means by which the South can increase its welfare. These conditions are also crucially related to the sign of $\frac{d\hat{R}}{ds}$ and hence to the value of Reserves in R&D. When $\frac{d\hat{R}}{ds} < 0$, strategic destruction is more likely where the North has low monopoly power ($\pi''(.)$ is small in absolute terms), where the marginal costs of seed production/R&D costs do not increase too rapidly ($c''(.)$ is small) and the intensive sector in the North (n) is small. These conditions can be understood easily. When $\frac{d\hat{R}}{ds} < 0$ and the North has minimal monopoly power it is less inclined to restrict seeds to the South making it easier for the South to coerce more seeds from the North. Furthermore, producing more seeds for the South is more likely where the marginal costs are not rising quickly, whilst the North is more inclined to encourage intensive production in the South where the opportunity cost of land in the North is higher, and hence the North's intensive sector is small. These incentives are reversed when $\frac{d\hat{R}}{ds} > 0$.

As described above, which of these cases arises depends upon the marginal value of Reserves ($\pi'(.)$). Again, the linear case of Example 2 provides a simple illustration of this point. The observant reader will have noticed that the same critical value for δ that determines the sign of $\frac{d\hat{R}}{ds}$ determines whether or not strategic destruction can be welfare enhancing for the South, i.e. the sign of $\frac{d\hat{s}}{dL_S}$. In short, only where Reserves have a low value (< 2), and where the intensive sector in the South encroaches upon the Reserve sector, will strategic destruction be viable in the linear case. The opportunity cost of land in the North is also important here. In Example 2 strategic destruction requires that the alternative use of land in the North yields positive marginal profit ($b > 0$). Where the opportunity cost of intensive production in the North is relatively high the North is encouraged to export seed to the South rather than produce domestically. If Reserves increase, intensive production is augmented and the North becomes increasingly inclined to increase land allocated to domestic intensive production rather than

³⁶This is in part due to that fact that when $\frac{d\hat{R}}{ds} > 0$ and $\frac{d\hat{p}}{ds}$ becomes smaller, and demand becomes more elastic in the South. In the extreme, where $\alpha > 4$, both $\frac{d\hat{R}}{ds}$ and $\frac{d\hat{p}}{ds} > 0$, i.e. the demand for seeds in the South is upward sloping. In this case the North cannot employ the optimal pricing policy and is bound to set a price which satisfies the South's participation constraint: $U_S \geq U_S^a$.

export seeds to the South. With $\frac{d\hat{R}}{ds} < 0$, the amount of seed that the South receives can fall as Reserves increase. The corollary of this is that, the South can reduce Reserves by employing strategic destruction and therefore induce the North to export more seeds, which at the margin is welfare enhancing.

In the linear case, where $\frac{d\hat{R}}{ds} > 0$, this incentive does not exist. However, in the general case the South may be able to exert what is a type of monopoly power on the North as measured by the second term in (4.31) even when $\frac{d\hat{R}}{ds} > 0$. In this case the North responds to the strategic destruction by supplying more seeds in an attempt to incentivise the conservation of Reserves, or at least halt the destruction.

This discussion gives us some insight into the solution to the biodiversity bargaining problem offered by the PPR model and how this solution might be preferred to Autarky despite reducing global welfare. It also explains the mechanism by which incentives for strategic destruction can be introduced in the South by the prevailing IPR institution, despite the potential for increased southern welfare. Clearly, the value of biodiversity contained in Reserves is of considerable moment in determining the bargaining incentives, regional welfare, and the extent to which this market can approximate the global optimal. The PPR model shows that the prevailing IPRs are likely to provide an inadequate mechanism to harness the global value of biodiversity and that this leads to an inefficient solution to the biodiversity bargaining problem. The inefficiencies arise not only due to the absence of direct remuneration for Reserves and the presence of monopolistic behaviour which can increase the conversion of Reserves, but also due to the scope for strategic destruction that this bargaining solution can introduce.

4.6 Conclusion

This paper has characterised the issue of North-South interactions concerning biodiversity conservation as one of cooperative bargaining. The interdependence, and therefore the need for cooperation between these regions is described in the context of R&D in the plant breeding sector of the biotechnology industry. Only if the two regions can cooperate in combining their unique resource endowments of human and natural capital and establish a satisfactory division of the surplus, can global welfare be maximised. Using cooperative bargaining theory allows us to analyse two institutions that have arisen in order to solve the biodiversity problem: the Convention on Biological Diversity (CBD) and the TRIPS agreement on intellectual property

rights and ultimately posit i) an additional and fundamental reason for the continued losses in primary forest observed even in the presence of these institutions and agreements, and in light of this ii) some prescriptive findings for these institutions.

Chief among the ideas presented here is that the institutions which attempt to solve the biodiversity bargaining problem actually introduce incentives for strategic destruction of biological resources by the South. I.e. in a manner similar to the 'rational threats' described by Nash (1953) the South has the potential to destroy its valuable reserves of biological resources as a strategic bargaining strategy. For the Nash bargaining case, where the South can influence this value for the North through the destruction of its residual biological reserves, we provide the conditions under which a destruction strategy is viable. What is more, we show that this strategy is largely invariant to the initial balance of bargaining power and is therefore potentially present at the extreme points of the bargaining frontier. The significance of these theoretical solutions is brought to light in the analysis of the bargaining solutions implied by the CBD and TRIPS and provides an answer to the following questions: Do existing institutions provide an agreed determination of this bargaining problem? Are these institutions efficient?

Firstly, the 'incremental cost' approach of the financial mechanism of the CBD, facilitated by the Global Environment Facility (GEF), can be interpreted as one of the end points of the family of optimal contracts: an extreme point contract. We show that the GEF reflects the North offering the South a contract for biodiversity preservation, which leaves the South no better off than in the absence of the contract. This indicates two things to us. Firstly, Southern indifference between the GEF contract and the conflict point may induce the South to use rational threats and employ destruction as a bargaining ploy. Indeed, such a response to the extreme point contract has been observed in Latin America with regard to the GEF (World Bank 2003). Consequently this approach is unlikely to represent a real solution to the biodiversity bargaining problem. We then show that the optimal contract should both compensate the South over and above incremental cost by making compensation reflect the stock of reserves, while specifying precisely the level of the Reserves in order to remove completely the incentives for strategic destruction. This recommendation is in line with previous work in this area (van Soest and Lensink 2000).

Secondly, another possibility is that the agreement regarding property rights to embodied innovation might provide the vehicle for solving the biodiversity bargaining problem. Intellectual Property Rights (IPRs) represent another important institutional mechanism for capturing

the value of biological diversity as an input to R&D. We analyse the prevailing property rights regime (PPR) where IPRs are located in the North, reflecting both the location of R&D and the relative strength of Northern IPRs in light of the TRIPS agreement. The PPR affords the North an advantage in bargaining with the South and facilitates cooperation largely on its own terms by acting as a monopolist in the market for seeds embodying innovations. This set up introduces a number of countervailing effects but the market for seeds facilitates the solution to the bargaining problem by transferring technology to the South and allowing the South to share in the cooperative gains. However, despite making the South better off than under the extreme point contract, we show that this outcome is inefficient for two reasons. Firstly, there are a number of countervailing distortions arising from the presence of a monopolistic North, the net impact of which depends extent to which intensive agriculture encroaches upon Reserves in the South. Secondly, the South may respond once more by asserting its sole source of bargaining power: the irreversible destruction of its biological Reserves. In either case the bargaining solution afforded by IPRs leads to an outcome within the bargaining frontier.

In conclusion, this paper shows how both the CBD/GEF and IPRs, and the allocation of bargaining power that these institutions imply, represent an inadequate mechanism for capturing the global value of biodiversity. Indeed, in conclusion, in describing global biodiversity conservation as a cooperative bargaining game, this paper alerts us to the idea that the very institutions that have arisen to generate North-South cooperation have the potential to exacerbate the losses of biodiversity and habitat that were the impetus for their creation.

4.7 References

Aghion, P., Howitt, P. (1992): A Model of Growth through Creative Destruction. *Econometrica* 60: 323-51

Angelsen, Arild and David Kaimowitz (1999): Rethinking the Causes of Deforestation: Lessons from Economic Models. *World Bank Research Observer*, vol. 14(1), pp. 73-98.

Barbier, E.B., Aylward, B.A. (1996): Capturing the Pharmaceutical Value of Biodiversity in a Developing Country. *Environmental and Resource Economics* 8:157-181.

Barbier E.B., J.C. Burgess and C. Folke (1994): *Paradise Lost? The Ecological Economics of Biodiversity*. London: Earthscan.

Barrett Scott (2003). *Environment and Statecraft*. Oxford University Press Inc, New York.

Barret Scott (2002a) Consensus Treaties. *Journal of Institutional and Theoretical Economics*. 158 (4).

Barrett Scott (1994a). Self Enforcing International Agreements. *Oxford Economic Papers*. 46. pp878 - 894

Barrett, Scott (1994): The Biodiversity Supergame *Environmental and Resource Economics*, vol. 4(1), pp. 111-122

Ben Porath E and Dekel E (1992): Signalling future actions and the potential for sacrifice. *Journal of Economic Theory* 57: 36-51.

Brown, G., Swierzbinski, J. (1988): Optimal Genetic Resources in the Context of Asymmetric Public Goods, in: Smith, V.K (ed): *Environmental Resources and Applied Welfare Economics*, RFF: Washington, 293-312.

Carraro, C., Katsoulacos, Y. and Xepapadeas, A. (eds): *Environmental Policy and Market Structure*. Dordrecht, pp.181-208.

Cervigni (1998). Incremental Cost in the Convention on Biological. *Environmental and Resource Economics*, 11, p217-241

Chichilnisky G. (1994): North-South Trade and the Global Environment. *American Economic Review*, 84(4), p851-874.

Chin, J.C. and G.M. Grossman (1990): Intellectual Property Rights in North-South Trade, in Krueger, A.O., Jones, R.W., (eds): *The Political Economy of International Trade. Essays in Honor of Robert Baldwin*. Cambridge, pp.90-108.

Copeland, B. R. (1990). Strategic enhancement and destruction of fisheries and the environment in the presence of international externalities. *Journal of Environmental Economics and Management*, 19(3), p213-226.

Craft, A. and D, Simpson (2001): The Value of Biodiversity in Pharmaceutical Research with Differentiated Products. *Environmental and Resource Economics* 18, 1-17.

Day-Rubinstein and Frisvold (2001): Genetic prospecting and biodiversity development agreements. *Land Use Policy* 18(3), pp.205-219.

Deardorff, A.V. (1992): Welfare Effects of Global Patent Protection. *Economica* 59: p35-51.

Deke, O. (2001): Conserving Biodiversity by Commercialisation? A Model Framework for a Market for Genetic Resources. *Kiel Institute of World Economics: Working Paper No 1054*.

Droege, S. and Soete, B. (2001): Trade-Related Intellectual Property Rights, North-South Trade and Biological Diversity. *Environmental and Resource Economics* 19: p149-163.

- Evenson, R. (1995). The Valuation of Crop Genetic Resource Preservation, Conservation and Use. Paper prepared for the Commission on Plant Genetic Resources, Rome.
- Gatti, R., Groom, B. Goeschl, T. and Swanson T. (2004). R&D, IPRs and genetic resource rights: an analysis of the North-South divide. *mimeo*.
- Goeschl, T., Swanson, T. (2002): The Social Value of Biodiversity for R&D. *Environmental and Resource Economics* 00:1-28.
- Goeschl, T and Swanson, T. (2003a): On Biology and Technology: The Economics of Managing Biotechnologies. The Fondazione Eni Enrico Mattei (FEEM) Note di Lavoro Series #42.03.
- Goeschl, T and Swanson, T (2003b). Pests, Plagues, and Patents. *Journal of the European Economic Association*. Vol 1(2), pp.561-575.
- Grossman, S., and Hart, O. (1986). The costs and benefits of ownership: a theory of vertical and lateral integration. *Journal of Political Economy* 94 (4), 691-719.
- Grossman G.M., Helpman A. (1991) *Innovation and Growth in the Global Economy*. Cambridge Press, Mass., London MIT.
- Helpman E (1993). Innovation, Imitation, and Intellectual Property Rights. *Econometrica* 61, p1247-1280.
- Heywood, V.H. (1998). *Global Biodiversity Assessment*. Published for the United Nations Environment Program. Cambridge University Press. Cambridge.
- Jones, J.C.H, Potashnik, T. and Zhang, A. (2001). Patents, Brand-Generic Competition and the Pricing of Ethical Drugs in Canada: Some Empirical Evidence from British Columbia, 1981-1994. *Applied-Economics*. June, 33(7), pp947-56
- Krugman, P (1979). A Model of Innovation, Technology Transfer, and the World Distribution of Income. *Journal of Political Economy*, Vol. 87 (2) pp. 253-66.
- Leakey, R and Lewin, R. (1995). *The Sixth Extinction*. Weidenfeld and Nicolson, London
- Levy M A (1993). European Acid Rain.: the Power of Trade Board Diplomacy. in P M Haas, R O Keohane and M A Levy (eds). *Institutions for the Earth: Sources of Effective Environmental Protection*. Cambridge MA: MIT Press.
- Margulis, Sergio (2004): Causes of deforestation of the Brazilian Amazon. World Bank working paper No. 22. Washington : The World Bank.
- Nash J (1953). Two-Person Cooperative Games. *Econometrica* Vol 21(1), pp128-140.
- Pearce D.W. and Moran D (1994). *The Economic Value of Biodiversity*. IUCN/World

Conservation Union/Earthscan

Petrin, A (2002). Quantifying the Benefits of New Products: The Case of the Minivan. *Journal-of-Political-Economy*. August, 110(4), pp705-29.

Rausser, G. and A. Small (2000): Valuing Research Leads: Bioprospecting and the Conservation of Genetic Resources. *Journal of Political Economy* 108(1), 173-206.

Schumpeter, J.A. (1942): *Capitalism, Socialism and Democracy*. New York: Harper and Bros.

Simpson, R.D., Sedjo, R.A. (1996): Valuation of Biodiversity for Use in New Product Research in a Model of Sequential Search. Discussion Paper 96-27 (July 1996), Resources for the Future, Washington D.C.

Simpson, R.D., Sedjo, R.A., Reid, J.W. (1996): Valuing Biodiversity for Use in Pharmaceutical Research. *Journal of Political Economy* 104(1): 163-185

Siqueira, K (2001). Common Agency and Partial Cooperation. *Journal of Public Economic Theory*. 3(3): p309-39.

Smith RJ, Muir RDJ, Walpole MJ, Balmford A, Leader-Williams N (2003): Governance and the loss of biodiversity, *Nature*, 426 (6962), pp. 67-70.

Southgate, Douglas; et al (2000): Markets, Institutions, and Forestry: The Consequences of Timber Trade Liberalization in Ecuador. *World Development* 28(11).

Swanson, Timothy (1996): The Reliance of Northern Economies on Southern Biodiversity: Biodiversity as Information. *Ecological Economics* 17(1), pp. 1-8.

Taylor, M.S. (1993): TRIPS, Trade and Technology Transfer. *Canadian Journal of Economics* 26: 625-637.

Ulph, A. and Ulph, D. (1996): Trade, Strategic Innovation and Strategic Environmental Policy - A General Analysis.

van Soest D.P. and Lensink R. (2000). Foreign transfers and tropical deforestation: What terms of conditionality?. *American Journal of Agricultural Economics*, 82 (May) pp389-399.

Vishwasrao, S. (1994): Intellectual Property Rights and the Mode of Technology Transfer. *Journal of Development Economics* 44:381-402

Vishwasrao, S. (1997): North-South Technology Transfer through Licencing. *International Trade Journal* 11:485-513.

Weitzman, M. (2000): Economic Profitability versus Ecological Entropy. *Quarterly Journal of Economics* 115(1), 237-263.

World Bank (2003). Contracting for Biodiversity Conservation in Agricultural Landscapes. Environment Department Paper No.96. Environmental Economics Series, World Bank.

Zigic, K. (1998): Intellectual Property Rights Violations and Spillovers in North-South Trade. *European Economic Review* 42:1779-1799.

4.8 Appendices

4.8.1 Appendix 1: Proof of Proposition 1

If South selects $(\tilde{n}, \tilde{s}, \tilde{t})$ and a transfer payment:

$$\begin{aligned}
 -T &= T_S(n, s : \tilde{n}, \tilde{s}, \tilde{t}) = \int_n^{\tilde{n}} [\pi(\tilde{R}) - b] dx - \int_{n+s}^{\tilde{n}+\tilde{s}} c'(x) dx + [U_N^a - (\pi(\tilde{R}) - b)\tilde{n} + c(\tilde{n} + \tilde{s}) - bL_N] \\
 &= [\pi(\tilde{R}) - b] (\tilde{n} - n) - c(\tilde{n} + \tilde{s}) + c(n + s) + [U_N^a - (\pi(\tilde{R}) - b)\tilde{n} + c(\tilde{n} + \tilde{s}) - bL_N] \\
 &= [\pi(\tilde{R}) - b] (-n) + c(n + s) + [U_N^a - bL_N]
 \end{aligned}$$

where $\tilde{R} = L_S - \tilde{t} - \tilde{s}$

North's utility is given by

$$\begin{aligned}
 U_N(n, s) &= [\pi(R) - b] n - c(n + s) + T_S(n, s) + bL_N \\
 &= U_N^a
 \end{aligned}$$

thus the North is indifferent between any level of n and s , including \tilde{n} and \tilde{s} . Introducing a, possibly tiny, penalty for deviation from the target levels specified would ensure compliance.

Given North selects \tilde{n} and \tilde{s} , the South's problem is to select (n, s, R, t) to maximise

$$\begin{aligned}
 U_S(n, s, R, t) &= \pi(R)s + t - k(t) - T_S(n, s : n, s, R) \\
 &= U^* - U_N^a = U^C + U_S^a
 \end{aligned}$$

Thus the South's optimisation problem is therefore equivalent to the Social Planners problem and hence the solution is the same, (n^*, s^*, R^*, t^*) .

b) The proof is equivalent for the other extreme point contract: If the North selects \tilde{s} and \tilde{t} :

$$\begin{aligned}
 T_N(t : \tilde{s}, \tilde{t}) &= \int_t^{t^a} [1 - k'(x)] dx - \pi(L_S - \tilde{s} - t)\tilde{s} \\
 &= [t^a - t] - [k(t^a) - k(t)] - \pi(L_S - \tilde{s} - t)\tilde{s}
 \end{aligned}$$

Then the South's utility is given by:

$$\begin{aligned}
U_S(t) &= \pi(L_S - \tilde{s} - t)\tilde{s} + t - k(t) + T_N(t : \tilde{s}, \tilde{t}) \\
&= U_S^a
\end{aligned}$$

Hence the South is indifferent to any level of t including \tilde{t} . Once again, a small penalty for deviation from \tilde{t} ensures compliance. Given the South selects \tilde{t} the North's problem is to select (n, s, R, t) to maximise:

$$\begin{aligned}
U_N(n, s, R, t) &= (\pi(R) - b)n - c(n + s) - T_N(t : s, t) \\
&= U^* - U_S^a = U^C + U_N^a
\end{aligned}$$

Once again, this is equivalent to the Social Planner problem and the solution is (n^*, s^*, R^*, t^*) .

4.8.2 Appendix 2: Proof of Example 1: Strategic destruction by the South

GENERAL FORMULATION:

$$\frac{dU_S^*}{dL_S} = \alpha \frac{dU_S^a}{dL_S} + (1 - \alpha) \frac{d(U^* - U_N^a)}{dL_S}$$

For $L_S > t^a$, from Equation (4.19) $\frac{dU_S^a}{dL_S} = 0$, and $\frac{dU_S^*}{dL_S} = (1 - \alpha) \frac{d(U^* - U_N^a)}{dL_S}$. Therefore for all $\alpha > 0$, $\frac{dU_S^*}{dL_S} \geq 0$ iff $\frac{d(U^* - U_N^a)}{dL_S} \geq 0$ and U_S^* is maximised when $(U^* - U_N^a)$ is maximised, irrespective of the value of α . From equations (4.13) and (4.10) and the Envelope Theorem:

$$\begin{aligned}
\frac{d(U^* - U_N^a)}{dL_S} &= \frac{\partial U}{\partial L_S}(n^*, s^*, t^*) - \frac{\partial U_N^a}{\partial L_S}(n^a, t^a) \\
&= \pi'(L_S - s^* - t^*)(n^* + s^*) - \pi'(L_S - t^a)(n^a)
\end{aligned}$$

and so

$$\pi'(\overline{L_S} - t^*)(n^a) > \pi'(\overline{L_S} - s^* - t^*)(n^* + s^*) \Rightarrow \frac{d(U^* - U_N^a)}{dL_S} < 0 \text{ at } \overline{L_S}$$

and destruction of arable land will increase Utility for the South. QED

For $L_S < t^a$, $R^a = 0$ and, from Equation (4.12), $\frac{dU_N^a}{dL_S} = 0$, so from Envelope Theorem:

$$\begin{aligned}
\frac{dU_S^*}{dL_S} &= \alpha \frac{dU_S^a}{dL_S} + (1-\alpha) \frac{dU^*}{dL_S} \\
&= \alpha(1 - k'(L_S)) + (1-\alpha)[\pi'(L_S - s^* - t^*)(n^* + s^*)] \\
&> 0
\end{aligned}$$

and the optimal solution is therefore to increase L_S up to t^a which is the Autarky solution.

PROOF OF EXAMPLE 1: >From Equation (4.14) & (4.15) we have $s^* = 0$ (as $b = 0$) and $n^* = \left(\frac{(L_S - t^*)^\delta}{\beta}\right)^{\frac{1}{\beta-1}} > 0$ when $L_N > n^*$.

Let $\Phi(L_S, t, n) = \pi'(L_S - t)(n) = \delta(L_S - t)^{\delta-1} \left(\frac{(L_S - t)^\delta}{\beta}\right)^{\frac{1}{\beta-1}} = \left(\frac{\delta}{\beta^{\frac{1}{\beta-1}}}\right) (L_S - t)^{\delta-1+\frac{\delta}{\beta-1}}$.

Destruction is beneficial to the South if, $\overline{L_S} > t^a = \left(\frac{1}{\gamma}\right)^{\gamma-1}$ and $\frac{d(U^* - U_N^a)}{dL_S} < 0$ at $\overline{L_S}$.

The last condition requires that $\Phi(\overline{L_S}, t^a, n^a) > \Phi(\overline{L_S}, t^*, n^*)$

$$\iff \left(\frac{\delta}{\beta^{\frac{1}{\beta-1}}}\right) (\overline{L_S} - t^a)^{\delta-1+\frac{\delta}{\beta-1}} > \left(\frac{\delta}{\beta^{\frac{1}{\beta-1}}}\right) (\overline{L_S} - t^*)^{\delta-1+\frac{\delta}{\beta-1}}$$

given that $t^a > t^*$, this inequality hold iff $(\delta - 1 + \frac{\delta}{\beta-1}) < 0 \iff \beta > \frac{1}{1-\delta}$

4.8.3 Appendix 3: Proof of Example 2.

Period 2: The South chooses s, t and R . The functional forms are $\pi(R) = \delta R$, $c(x) = \beta x^2$, $k(t) = t^2$. This yields an expression for the South's utility as follows:

$$U_S = \delta R + t - t^2 = \delta(L_S - t - s) + t - t^2 \quad (4.34)$$

The first order conditions for maximisation yield:

$$\hat{t} = \frac{1 - \delta \hat{s}}{2}, \quad \hat{R} = L_S - \frac{1}{2} + \left(\frac{\delta}{2} - 1\right) \bar{s} \quad (4.35)$$

and the inverse demand curve for s faced by the monopolist is,

$$p(s) = \delta(L_S - t - \bar{s}) - \delta \bar{s} = \delta \left(L_S - \frac{1}{2}\right) + 2 \left(\frac{\delta}{4} - 1\right) \delta \bar{s} \quad (4.36)$$

The second order conditions are as follows:

$\frac{d^2 U_S}{dt^2} = \pi''(L_S - t - s)s - k''(t) = -2$, $\frac{d^2 U}{ds^2} = \pi''(L_S - t - s)s - 2\pi'(L_S - t - s) = -2\delta$, $\frac{d^2 U_S}{ds dt} = \pi''(L_S - t - s)s - \pi'(L_S - t - s) = -\delta$, $\left(\frac{d^2 U}{dt^2}\right)$ therefore $\left(\frac{d^2 U}{ds^2}\right) - \left(\frac{d^2 U}{ds dt}\right)^2 = 4\delta - \delta^2 > 0$ as required.

It is interesting to note that $\frac{d\hat{R}}{d\bar{s}} > 0$ if $\delta > 2$, i.e. the North will provide seed to the South as a means of incentivising the provision of Reserves in the South. Even if this is not satisfied the North may still want to provide seed to provided that p sufficiently high.

Case 1: $\hat{t} > 0$, i.e. $\bar{s} < \frac{1}{\delta}$:

$$\begin{aligned} U_S &= (\delta R - p)\bar{s} + t - t^2 = \left(\delta \left(L_S - \frac{1}{2} + \left(\frac{\delta}{2} - 1 \right) \bar{s} \right) - \delta \left(L_S - \frac{1}{2} \right) - \left(\frac{\delta}{2} - 2 \right) \delta \bar{s} \right) \bar{s} \\ &\quad + \frac{1 - \delta \bar{s}}{2} - \left(\frac{1 - \delta \bar{s}}{2} \right)^2 \\ &= \frac{1}{4} + \delta \bar{s}^2 \left(1 - \frac{\delta}{4} \right) \end{aligned}$$

So $U_S \geq \frac{1}{4} = U_S^a$ is the participation constraint for the South and whenever $\bar{s} > 0$ and $\delta < 4$, it follows that $\frac{dU_S}{d\bar{s}} > 0$ and $U_S > U_S^a$ as suggested in Proposition 3.

Case 2: $\hat{t} = 0$, $\bar{s} \geq \frac{1}{\delta}$.

If $\delta < 4$, then $p(s) = \delta L_S - 2\delta \bar{s}$, $\hat{R} = L_S - \bar{s}$ and

$$U_S = (\delta \hat{R} - p)\bar{s} = (\delta(L_S - \bar{s}) - \delta L_S + 2\delta \bar{s})\bar{s} = \delta \bar{s}^2 > \frac{1}{\delta} > \frac{1}{4} = U_S^a$$

If $\delta > 4$, then the North must set the price in order to maximise profits given the binding participation constraint. I.e. the North must set the price to ensure that $U_S = U_S^a = 1/4$. The pricing formula then becomes:

$$\begin{aligned} (\delta \hat{R} - p)\bar{s} &= (\delta(L_S - \bar{s}) - p)\bar{s} = \frac{1}{4} \\ p(s) &= \delta(L_S - \bar{s}) - \frac{1}{4\bar{s}} \end{aligned}$$

We do not consider this case further here. See Gatti et al (2004) for a deeper discussion.

Strategic Destruction:

Proposition 4 shows that for strategic destruction requires that $\frac{dU_S}{dL_S} < 0$, and that a necessary condition in the linear case where $\delta < 4$ and $\frac{dU_S}{d\bar{s}} > 0$ is that $\frac{d\bar{s}}{dL_S} < 0$ ³⁷. In order to the conditions in which this can occur we need an expression for \bar{s} .

Period 1: The North chooses \hat{s} and \hat{n} Remembering that $\pi(R) = \delta R$ and $c(n + s) = \beta(n + s)^2$, we have:

$$U_N = (\delta R^* - b)n + p^*(s)s - \beta(n + s)^2 + bL_N$$

³⁷When $\alpha > 4$, $\frac{dU^*}{d\bar{s}} = 0$, strategic destruction has no direct impact on South's utility but could perhaps be used to 'bargain' over price p . This goes beyond this particular paper however.

Case 1: $\hat{t} > 0$, i.e. $\bar{s} = \hat{s} < \frac{1}{\delta}$:

The North's utility is given by:

$$U_N = \left(\delta \left(L_S - \frac{1}{2} + \left(\frac{\delta}{2} - 1 \right) s \right) - b \right) n + \left(\delta \left(L_S - \frac{1}{2} \right) + 2 \left(\frac{\delta}{4} - 1 \right) \alpha s \right) s - \beta(n + s)^2 + bL_N$$

The first order conditions give us the following solutions for \bar{s} and \hat{n} :

$$\hat{n} = \frac{\left(\left(\frac{\delta}{2} - 1 \right) \delta - 2\beta \right) \hat{s} + \delta \left(L_S - \frac{1}{2} \right) - b}{2\beta} \quad (4.37)$$

and:

$$\hat{s} = \frac{\delta \left(\frac{\delta}{2} - 1 \right) \hat{n} + b}{\delta \left(3 - \frac{\delta}{2} \right)} \quad (4.38)$$

$\frac{d^2 U_N}{dn^2} = -2\beta < 0$, $\frac{d^2 U_N}{ds^2} = (\delta - 4)\delta - 2\beta < 0$, $\frac{d^2 U_N}{dsdn} = \delta \left(\frac{\delta}{2} - 1 \right) - 2\beta$, and $\left(\frac{d^2 U_N}{dsdn} \right) \left(\frac{d^2 U_N}{ds^2} \right) - \left(\frac{d^2 U_N}{dsdn} \right)^2 = 4\beta^2 + 2\delta\beta(4 - \delta) - (\delta^2 \left(\frac{\delta}{2} - 1 \right)^2 - 4\delta\beta \left(\frac{\delta}{2} - 1 \right) + 4\beta^2) = 4\delta\beta - \delta^2 \left(\frac{\delta}{2} - 1 \right)^2$. So maximisation requires that $4\delta\beta - \delta^2 \left(\frac{\delta}{2} - 1 \right)^2 > 0$, or $\beta > \left(\frac{\delta}{2} \left(\frac{\delta}{2} - 1 \right) \right)^2$. Solving out for \hat{s} and \hat{n} yields:

$$\hat{s} = \frac{\delta^2 \left(\frac{\delta}{2} - 1 \right) \left(L_S - \frac{1}{2} \right) + b \left(2\beta - \delta \left(\frac{\delta}{2} - 1 \right) \right)}{\left(4\delta\beta - \left(\delta \left(\frac{\delta}{2} - 1 \right) \right)^2 \right)} \quad (4.39)$$

and:

$$\hat{n} = \frac{\delta \left(3 - \frac{\delta}{2} \right) \hat{s} - b}{\delta \left(\frac{\delta}{2} - 1 \right)} \quad (4.40)$$

PROOF OF EXAMPLE 2. From above strategic destruction requires $\frac{d\hat{s}}{dL_S} < 0$. In the linear case:

$$\frac{d\hat{s}}{dL_S} = \frac{\delta^2 \left(\frac{\delta}{2} - 1 \right)}{\left(4\delta\beta - \left(\delta \left(\frac{\delta}{2} - 1 \right) \right)^2 \right)}$$

Given the second order conditions the denominator is positive, so $\frac{d\hat{s}}{dL_S} < 0$ requires that $\delta < 2$. For an interior solution a number of other restrictions need to be placed upon the parameters. Given (4.39) for $\hat{s} < \frac{1}{\delta}$, and hence $\hat{t} > 0$ we have:

$$b < \frac{\left(4\beta - \delta \left(\frac{\delta}{2} - 1 \right)^2 \right) + \delta^2 \left(1 - \frac{\delta}{2} \right) \left(L_S - \frac{1}{2} \right)}{\left(2\beta + \delta \left(1 - \frac{\delta}{2} \right) \right)} \quad (4.41)$$

Given (4.40) some algebra gives us that $\hat{n} > 0$ requires:

$$b < \frac{\delta \left(3 - \frac{\delta}{2}\right) \delta^2 \left(1 - \frac{\delta}{2}\right) \left(L_S - \frac{1}{2}\right)}{(\delta\beta(2 - \delta) + \delta^2 \left(1 - \frac{\delta}{2}\right)(4 - \delta))} \quad (4.42)$$

Hence, if $\delta = 1$ the second order condition requires $\beta > \frac{1}{16}$. Then $\hat{s} > 0$, requires $b > \frac{\delta^2(1-\frac{\delta}{2})(L_S-\frac{1}{2})}{(2\beta+\delta(1-\frac{\delta}{2}))} = \frac{(\frac{1}{2})(L_S-\frac{1}{2})}{(2\beta+(\frac{1}{2}))} = \frac{(L_S-\frac{1}{2})}{4\beta+1}$, and $\hat{n} > 0$, requires $b < \frac{\delta(3-\frac{\delta}{2})\delta^2(1-\frac{\delta}{2})(L_S-\frac{1}{2})}{(\delta\beta(2-\delta)+\delta^2(1-\frac{\delta}{2})(4-\delta))} = \frac{\frac{5}{4}(L_S-\frac{1}{2})}{\beta+\frac{3}{2}} = \frac{5(L_S-\frac{1}{2})}{4\beta+6}$

(Note: $\frac{5(L_S-\frac{1}{2})}{24\beta+14} > \frac{(L_S-\frac{1}{2})}{16\beta+2}$ when $\beta > \frac{1}{16}$ and $L_S > \frac{1}{2}$. Hence if we let $\beta = \frac{1}{4}$ we have $\hat{s} > 0$ and $\hat{n} > 0$ when $\frac{(L_S-\frac{1}{2})}{2} < b < \frac{5(L_S-\frac{1}{2})}{7}$. For $\hat{s} < \frac{1}{\delta}$ we need:

$$b < \left(\frac{3}{4}\right) + \frac{1}{2} \left(L_S - \frac{1}{2}\right)$$

Thus strategic destruction possible if, for example, $\delta = 1, \beta = \frac{1}{4}, b = \frac{1}{3}$ and $L_S = 1$.

Chapter 5

The Sloping Lands Conversion Policy of the People's Republic of China: Impacts on income, income distribution and poverty alleviation

Abstract¹

This chapter investigates the impact of the Chinese Government's Sloping Lands Conversion Programme (SLCP), or 'Grain for Green' policy. The primary objectives of the programme are to reduce environmental costs in river basins e.g. flooding, erosion and sedimentation of watercourses, and to alleviate rural poverty. To meet these objectives relatively generous yet temporary compensation is given to farmers for reforesting currently cultivated land on steep hillsides. Certainly there has been much reforestation under the SLCP, but what has been the impact of the programme on participants? In this chapter we employ programme evaluation methods (e.g. Heckman et al 1997, Blundell and Costa-Dias 2000) to estimate the impact of the SLCP upon household incomes and poverty alleviation, while correcting for the selection bias that plagues previous analyses. We use a variety of matching difference in differences methods (Heckman 1997, Abadie 2005, Athey and Imbens 2003) to estimate average and quantile treatment effects, each of which accommodates the potential for heterogeneous household responses to interventions as predicted by theory and witnessed in rural China and beyond (e.g. Chen and Ravallion 2003, Key et al 2000). Given this heterogeneity, and the dispute surrounding the appropriate measure of poverty in China, we estimate the impact on poverty alleviation for a wide range of poverty lines. Lastly, in light of concern that the impact of the programme, like the compensation, will be merely temporary, we use the results of our analysis to say something about the sustainability of the programme once compensation ceases.

¹The author would like to thank the Chinese Council for International Cooperation for Environment and Development for funding this research. The survey and research agenda would not have been possible without the vision and hard work of Professor Zhang Shiqiu at Beijing University and my supervisor Pr. Tim Swanson. Furthermore, the survey itself and its specific focus was the result of discussions between Dr Andreas Kontoleon and Pauline Grosjean at the Universities of Cambridge and Toulouse respectively. Indeed, this chapter has arisen out of numerous discussions with Pauline Grosjean. Many thanks also to all the student enumerators at the Department of Environmental Sciences at Beijing University for their hard work and commitment in helping to develop and implement the survey during the summer of 2004. Lastly, thanks to Jerry Warford for being the catalyst for my involvement in this project.

5.1 Preamble

The previous Chapter focussed upon the nature of international agreements in biodiversity conservation and the extent to which they may introduce perverse incentives for eligible countries. Therein, and by way of anecdotal evidence, the World Bank's experience in Latin America was cited. Incremental cost contracts in which the compensation offered effectively covered only marginal changes in agricultural production, and not stocks of forest land as yet unconverted, were received by farmers with a certain amount of contempt: 'bueno corto todo!' (right, I'll cut the lot!) being a common response (World Bank 2003). Clearly the amount of compensation at the level of the individual farmer is of particular importance for ensuring the sustainability of policies which aim to curtail deforestation or encourage reforestation. The message here is that not only will farmers have to be compensated for any loss of income, but compensation schemes must endeavour to improve incomes among participating farmers, sometimes elevating them from poverty, in order for such a policy to achieve its objectives in the long run. Of course, poverty alleviation is the prime objective of some interventions, particularly in developing countries, and in this regard the policy prescription in Chapter 4 appears to satisfy both environmental and poverty alleviation objectives: the north-south distribution of income under the no-destruction bargaining solution described in the previous Chapter is more equal and ensures greater preservation of environmental and biological resources. Beyond this, the link between environment and poverty is well established, and is particularly strong in developing countries, and initiatives exist originating from international organisations, national governments or more locally, which endeavour to achieve both environmental and poverty alleviation objectives by compensating households for land set-asides (World Bank 2003, Johnson et al 1997, CCICED 2002). But how successful have these policies been in alleviating poverty at the household level and maintaining environmental benefits? What are the features of the programme and the households that determine success? More generally, how can one adequately and robustly estimate programme impacts? These are the questions to which we turn in this Chapter. In particular we address the largest national set-aside compensation programme in the world: the Sloping Lands Conversion Programme (SLCP) of the People Republic of China, or 'Grain for Green'.

5.2 Introduction

In this Chapter we analyse an important national reforestation compensation scheme: the Sloping Lands Conversion Programme (SLCP) or 'Grain for Green' programme of the Peoples Republic of China. This policy started in 1999 and has two main objectives. Firstly, and primarily, the SLCP intends to generate river basin/watershed related environmental benefits by reforesting currently cultivated highly sloped land in the upper reaches of a number of important river systems. Indeed, the SLCP was hatched in direct response to the loss of topsoil, siltation of streams and the increased flood events witnessed in many river basins in recent years, most notably the Yangtze River and the Chao and Bai rivers in the North East of China, each of which was subject to severe floods in the summer of 1998. The blame for the severity of these floods was placed squarely with deforestation (World Bank 2001). Secondly, the SLCP endeavours to alleviate rural poverty, by offering relatively generous compensation packages to households for reforestation of their cultivated land in the form of cash, in-kind grain and occasionally tree-seedlings and technical assistance (Xu et al 2001).

The compensation provided to households under the SLCP is limited in duration to a period of 5 or 8 years, and for this reason, there is great speculation as to whether or not the SLCP will be sustainable in the long-run with regard to its two main objectives: environmental benefits and poverty alleviation (Uchida et al 2004, Xu and Cao 2002, Gong and Xu 2000, CCICED 2000). Of course, these two goals are inexorably linked since participating households will only maintain lands reforested under the SLCP if their welfare in the period after compensation ceases is at least what it was under their former land-use practices. That is, the sustainability of the SLCP requires that the incomes of the poor households that are the stated focus of the programme are permanently raised as a result of the temporary subsidies, and hence some households will need to be lifted permanently out of poverty. But is this likely to happen and if so, how?

Ultimately, the implied hope among policy makers within the Chinese government in this regard is that temporary compensation for setting aside land will enable households to find alternative and more lucrative sources of income which permanently raise household welfare thereby removing incentives to revert back to their former practices when compensation ceases. One obvious way in which increased welfare is envisaged is through the production of forest goods from the forested SLCP land. Other alternatives include increased livestock production

or off-farm income.

So, the sustainability of the environmental benefits from the SLCP and the permanent alleviation of rural poverty rests upon the validity the assertion that temporary subsidies will induce permanent changes in the source and level of household income. But, what impact has the SLCP had upon the incomes of participant households to date? The empirical evidence in relation to this question is scant thus far and subject to numerous caveats and empirical problems. Uchida et al (2004), for example, provide an analysis of these impacts but only for participants. Although their results are indicative they lack a proper counterfactual comparison group of non-participants and only reflect impacts over a short adjustment period of one to two years. Since selection into the programme is likely to be non-random, their estimates of impacts are likely to be contaminated with selection bias, while their data may not cover a time-span sufficient for household responses to be manifested. Similarly, the idea that households will maintain SLCP land in the absence of subsidies is certainly at loggerheads with empirical (and anecdotal) evidence on participant households' post-programme intentions. Uchida et al (2004) and Grosjean (2005) show that many households intend to revert back to former practices upon the cessation of compensation, while others believe that the compensation will simply continue indefinitely². On the positive side, the latter study has shown a link between participation in the off-farm labour market and the propensity to maintain SLCP land once compensation ceases. However, while this is an important finding, in the presence of issues of selection into the programme, the extent to which participation in the programme has facilitated increases in off-farm labour incomes is not altogether clear. Consequently, the assumption that such changes will occur as a result of the SLCP remains heroic. For these reasons alone it remains an important task to analyse the impact of the programme on the level and composition of household incomes and poverty alleviation.

In light of this, the questions we wish to answer in this Chapter are as follows. Firstly, given the various attributes that influence participation, to what extent has this highly targeted policy selected poor households and increased their incomes compared to non-participants? How has the composition of income changed? and to what extent has the impact been sufficient to lift participant households out of poverty?. The latter naturally gives rise to a further question; Against which yardstick are we to measure poverty alleviation? This is particularly pertinent

² Anecdotal evidence obtained by colleagues at Beijing University from Sichuan province suggests that some households will almost certainly reconvert SLCP forest upon cessation of the compensation.

in the case of China since, not only is the appropriate choice of poverty measure in China the source of some considerable disagreement, research has shown that the impact of other poverty alleviation strategies in China can be hidden by the choice of poverty line (Chen and Ravallion 2003).

In order to answer these questions and obtain unbiased and efficient estimates of the impact of the SLCP there are two econometric issues arising from particular features of the intervention and its target group. Firstly, as mentioned, there is the question of selection for participation in the SLCP. While in principle participation in the programme is voluntary, evidence suggests that whether selection is voluntary, compulsory or a mixture of the two, depends upon location. In each case selection is likely to be non-random and based on household and local characteristics that are not always observable to the analyst. Hence, the econometric approach must provide an identification strategy that accounts for this. Secondly, it is well known that there are local and household level determinants of rural poverty (see e.g. Jalan and Ravallion 2002, Park et al 2002) and also that semi-subsistence households differ in the nature and severity of the constraints, frictions and market failures that they face, and which effectively define them (Key et al 2000). Consequently, responses to public interventions such as the SLCP are likely to be extremely heterogeneous both geographically and at the household level. Indeed, this type of heterogeneity underlies the results of Chen and Ravallion (2003) since they imply that the impact differs across quantiles of the income distribution. It is clear therefore that any empirical approach which attempts to estimate programme impacts needs to accommodate observable and unobservable heterogeneity in two dimensions: selection into the programme and in the specification of the impact.

In order to answer these questions in a manner which accounts for the aforementioned issues of heterogeneity and selection we draw from the programme evaluation literature and employ a variety of techniques. The analysis of the impact of public interventions has fostered a burgeoning literature on programme evaluation and although it derives predominantly from the statistical and epidemiological literature, in economics at least, it has developed methodologically in the realm of the evaluation of active labour market programmes³. The overriding goal of the techniques applied to non-experimental data is to emulate a randomised control experiment and thereby overcome the issues described above which are commonly referred to as the 'programme evaluation problem': the fact that we are missing data on what would have

³See e.g. Blundell and Costa-Dias 2002, Heckman and Robb 1995, Heckman et al 1997 for excellent reviews.

happened to participants had they not participated means that we cannot easily evaluate the real impact. These methods have been applied widely in the analysis of major public and donor interventions in China (e.g. Chen and Ravallion 2003, Park et al 2002) and in other developing countries (e.g. Henschel 2002, Bandyopadhyay et al 2004).

In this Chapter we take the following empirical approach. Our parameter of interest in the first instance is the ‘average treatment on the treated’ (*ATT*), that is, the average impact of the SLCP upon participants. We estimate this parameter for household income and the components thereof using the panel structure of the data to account for selection on unobservable heterogeneity. We use propensity score matching methods following Heckman et al (1997) and an estimator weighted by the propensity score following Abadie (2005) to control for selection on observables. Then, mindful that average impacts may hide heterogeneous impacts at different quantiles of the income distribution, and given our interest in the impact at lower income quantiles, we estimate Quantile Treatment Effects (*QTE*) following Lehman (1972), Koenker (2003) and Athey and Imbens (2005). Lastly, we estimate the impact of the programme on poverty alleviation, that is, the proportion of households living beneath the poverty line, for a variety of poverty lines commonly employed in China. This analysis draws from Chen and Ravallion (2003). In this way we establish the average impact of the programme and the extent to which the programme has been pro-poor. Finally, using these results we say something about the sustainability of the programme once compensation ceases and highlight future work.

We undertake our analysis of the SLCP using household level data gathered specifically for this purpose by the Department of Environmental Sciences at Beijing University, in collaboration with the Department of Economics at the University College London during the summer of 2004 in two distinct areas of China: Ningxia in the arid North and Guizhou in the more humid South. This Chapter is organised as follows. In Section 5.3 we describe the SLCP in some depth and the previous work that has been undertaken in this area. Section 5.4 discusses the issues of heterogeneity and selection while Section 5.5 describes the programme evaluation problem and the matching Difference in Differences estimators that we use to address these issues. Section 5.6 describes the empirical strategy, the data, presents the behavioural model for participation in the SLCP and provides an analysis of this decision. In Section 5.7 we present the Difference in Difference estimates of the average treatment on the treated (*ATT*) for income measures. The analysis of the impact upon income distribution and poverty alleviation occurs in Section 5.8, with an analysis of income quantiles and quantile treatment effects (*QTE*) in Section 5.8.1

and poverty alleviation in Section 5.8.2. Section 5.9 discusses and concludes.

5.3 The Sloping Lands Conversion Policy (SLCP)

5.3.1 Motivation and compensation

The Sloping Lands Conversion Policy represents an ambitious intervention to encourage reforestation of previously converted land by compensating farmers for changes in land use practices on sloping and other types of land. The proposed scale of the project is huge with the ultimate aim being the conversion of around 15 million hectares of cropland, approximately a third of which will be on land which has a slope of at least 25 degrees (Uchida et al 2004, CCICED 2002). Since the policy commenced in 1999 approximately 15 million farmers have become participants in 20 provinces and over 27000 villages (Uchida et al 2004). In the first 2 years of the SLCP almost 1.2 million hectares of cultivated land was converted to forestland or pasture, while an additional 1 million hectares of barren land was afforested.

The principle motivation for this large and expensive intervention is to address environmental damages associated with the cultivation of sloped lands. There is considerable evidence to suggest that the main cause of increased runoff and soil erosion in China is deforestation in the upper reaches of river basins and watersheds. This leads to a number of important costs which are incident throughout the watershed. Firstly, the severe flooding in the Bai, Chao and particularly the Yangtze river basins in 1998, which imposed considerable costs on downstream authorities and inhabitants, has been attributed to the denuding of formerly forested hillsides in the upper reaches of these basins. In both upstream and downstream areas the loss of fertile topsoil, the siltation of streams and reduced hydraulic capacity of the watercourses has inhibited the productivity of agriculture, the availability of water resources and contributed to the increased incidents of flooding. In some areas the river level at its peak is 7m higher than its historical river bank and in the Yangtze River alone investments of up to Y7.8 billion have taken place in order to mitigate this problem (Yang 2001) . In order to address these watershed costs the SLCP's stated objective is to target highly sloped lands. However, the environmental costs of such cultivation in general are not limited to watersheds but also include airsheds. The increased incidence of dust-storms in the Northern plains, and the associated loss of topsoil that this entails, has also been attributed to the extensive cultivation of former pastures or natural grasslands and, despite its name, the SLCP has targeted these flatter areas with the purpose of

returning the land to pasture or its natural grassland state (CCICED 2002). In this Chapter we focus upon the aspects of the SLCP that are concerned with reforestation.

The compensation takes on a number of different forms and levels and is of a duration which depends upon the type of forest to which land is converted. Firstly, compensation can consist of cash, grain or seedlings for trees provided by the local forest agencies. Depending upon particular circumstances, SLCP participants receive approximately 1500 to 2250 kilograms of grain per hectare per year and an additional Y300 per mu per year in cash⁴. Lastly, seedlings are provided on a per hectare basis. These general levels of compensation vary from region to region reflecting local conditions. In the Guizhou and Ningxia, the regions studied in this Chapter and in Uchida et al (2004), the level of the annual cash compensation was Y300 and Y200 per mu respectively. These differences reflected the different opportunity costs of land encountered in each region. Uchida et al (2004) report that the compensation varies over time as well as space with the total value of compensation in the upper and middle reaches of the Yellow river varying from Y3150 per hectare in the first year of the programme, to Y2400 in the second year. In the Yangtze River basin annual compensation varied from Y4200 per hectare in the first year to Y3450 from the second year on. These variations over time reflect the initial fixed start-up costs while the variation over space reflects the productivity of land in regions with different climatic and agronomic characteristics. Uchida et al (2004) have analysed the extent to which these regionally fixed compensation levels lead to the prevalence of under or over compensation. They find that in general over compensation prevails and suggest that the same environmental benefits could be achieved at a lower cost. However, Ng and Pearce (2005) note that reductions in compensation in the name of cost effective environmental benefits must be tallied against the potential losses in poverty alleviation.

The policy varies across participants with regard to the duration of the compensation. Cultivated sloped land is converted either to 'ecological' forest or to 'productive' forest. In the former case the farmer has no rights whatsoever to the products that the forest has to offer: e.g. timber, while the role of custodian of such forests is generally assumed (CCICED 2002). In this case land is converted to forest which serves a purely ecological function and compensation continues for a period of 8 years. For productive forests participants are allowed access and have property rights to the forest products: non-timber forest products: fruits, nuts mushrooms etc., and limited quantities of timber. In this case there is potential for the farmer

⁴1 hectare = 15 *mu*.

to replace income lost from cultivation of crops once trees become productive and for this reason compensation continues for a period of 5 years only, reflecting time required for trees to become productive (Xu et al 2000). The rules of the SLCP state that a minimum of 80% of the reforested area in any region must be ecological forest. Once more, there is a trade-off here between encouraging more commercial or productive forests at the expense of environmental benefits, and encouraging more ecological forests to the potential detriment of incomes, poverty alleviation and hence the long-run sustainability of the programme.

5.3.2 Implementation and institutions

The SLCP is implemented via a number of governmental bodies. Subsidies stem from central government and are distributed by local government bodies at the county and village level. Local government is also responsible for inspections and other assistance in relation to the programme, such as provision of seedlings and certain technical assistance (Ng and Pearce 2005). As mentioned above, the implementation of the SLCP by local government varies from place to place. Perhaps the most important aspect of this is the selection of the participants which, as already mentioned, differs in the extent to which it is voluntary from one village to the next. Furthermore, the emphasis of the programme differs with some villages focussing upon the poverty alleviation objective of the SLCP and other focussing upon the environmental benefits. It is also worth noting that in some areas the implementation of the SLCP has outpaced the arrival of funds, leading to some additional hardship for participants (Ng and Pearce 2005).

At the plot level the property rights to land and the management responsibility of forested land also varies from place to place. The most important distinction here is between household management under the Household Responsibility System (HRS) and collective management⁵. Similarly, there is frequently local government intervention at the plot level where village leaders or members of the implementation agency choose the plots to be included in the SLCP and the frequently the type of trees (Uchida et al 2004). Lastly, in line with the literature on the SLCP, our survey reveals that, while this is not necessarily a built in feature of the SLCP, there is some uncertainty with regard to the property rights to land converted under the SLCP and

⁵The HRS was introduced in the early 1980's and represented a shift in the property rights to land from local government or collective ownership and management towards households. It is widely regarded that this shift increased the perceived security of property rights to land and invoked important increases in agricultural productivity (e.g. Dong 1996).

the associated products.

5.3.3 Previous analyses of the SLCP: Results and shortcomings

Since 1999, there have been remarkably few attempts to evaluate the impact of the SLCP and its effectiveness and efficiency in reaching the stated objectives. The focus of these early studies has been upon the types of land targeted by the SLCP, its cost-effectiveness, the effect on incomes and consequently the extent to which the SLCP is sustainable (Uchida et al 2004, WWF 2003, Xu et al 2002). In particular, these studies highlighted the marketability of tree varieties in productive forests or the development of markets for such goods as being major determinants of poverty alleviation and sustainability of the SLCP. Institutions such as property rights to SLCP land, security of which generally encourages investment in the maintenance of the re-forested lands, were also highlighted. Investment in SLCP land, it is argued, would increase the opportunity cost of reforested land over cropland and hence reduce the incentives to revert back. There is also evidence to suggest that farmers' income has indeed increased as a result of their participation in the SLCP (CCICED 2002). This is attributed to two facts. Firstly, on average at least compensation has outstripped the value of lost production. For example, Uchida et al (2004) estimate that in purchasing power parity terms the value of the compensation offered under the SLCP is up to fifteen times that offered to farmers under the US Conservation Reserve Programme (CRP)⁶. Secondly, Uchida et al (2004) and Grosjean (2005) report that participation in the SLCP has indeed invoked the reallocation of labour towards more lucrative off-farm activities. On the other hand, preliminary evidence from the China Council for International Cooperation on Environment and Development (CCICED 2002) suggests that poorly defined property rights to reforested lands has so far hindered investment in forestry related production activities which in turn has hindered the provision of ecological services and the sale of non-timber forest products.

In light of these results it is not easy to draw general conclusions with regard to the impact and sustainability of the SLCP. On the one hand incomes have been increased and labour has been reallocated, apparently to more lucrative activities. While on the other, institutional deficiencies appear to be hindering income generation, poverty alleviation and hence sustainability. Furthermore, the empirical studies that have been undertaken to date suffer from a number of inadequacies which render their conclusions at least incomplete and at most highly suspect.

⁶This is a land set-aside programme of equivalent size in the US.

For example, although Uchida et al (2004) undertook a survey of 190 households in two distinct regions in order to evaluate the impact of the SLCP, they only collected data on SLCP participants. Hence their conclusions are drawn on the basis of participants alone and no control is made for any changes in the outcome variables of interest: incomes, prices, wages etc., among non-participants. In a sense which will be described more clearly below, any measure of programme impacts calculated without reference to a control group is likely to be contaminated with Section bias. Furthermore, previous analyses of income changes are weakened by the data used to construct the cropping incomes, and hence the opportunity cost of land converted under the SLCP. The prices used were obtained from a secondary source from different regions of China (Sichuan and Shaanxi) chosen due to their similar agro-climatic conditions (de Brauw et al 2002). Furthermore, previous analyses (Uchida et al 2004 and Gong and Xu 2002) obtained data on the impacts over a one to two year period after the implementation of the SLCP. It is arguable as to whether this represents a sufficiently long time period for participant households to make permanent changes in the pattern of production. A longer time horizon is likely to provide a clearer picture. Lastly, the former studies of the SLCP do not pay specific attention to the impact of the programme upon income distribution or poverty alleviation, one of the most important objectives of the programme.

The following Section describes how the data available to us allows us to overcome many of these shortcomings and inadequacies. It also describes the objectives of the study in more detail in light of the preceding discussion.

5.4 Issues for Estimation of SLCP Impact

5.4.1 Heterogeneity, selection and measurement of poverty alleviation

Assuming that the government of the Peoples Republic of China (PRC) wants to ensure permanent increases in income for participant households and hence sustained environmental benefits, the limited horizon of the programme implies that the government views the world in one of two ways. Either the government intends to extend the duration of the compensation once the currently specified period is over, or, there is the implicit hope that the duration of the temporary subsidies is sufficient to invoke permanent increases in participants' income thereby eradicating any incentive for participants to revert back to their former production patterns once compensation ends. The latter view is seen in the rules of the SLCP, which state the duration of the

compensation scheme explicitly and that the duration for productive forests is shorter than for ecological forests. That is, in the latter case, more time is allowed for participants to adjust and find alternative sources of income. The sustainability of the SLCP in meeting its poverty alleviation and environmental objectives rests upon this fundamental underlying assertion and the ability of households to find alternative sources of income.

It is clearly important to shed some light on whether this underlying assertion bears any resemblance to the actual impact of the programme four years on, and this is our over-arching objective in this Chapter. The previous Section has described the shortcomings of the previous analyses of the SLCP. However, there are a number of other features of the programme, its target group and its objectives that need to be addressed in order for us to identify econometrically the parameters of interest.

Firstly, it will be important to take into consideration the heterogeneous local and household level characteristics which determine both household income and poverty as well as their responses to interventions. Previous work has shown the importance of both household and local characteristics in determining outcomes in rural areas. In China, Jalan and Ravallion (2002) find strong evidence to show that local public goods: e.g. roads and natural resources, are the most significant determinant of geographical poverty traps. Other studies highlight the importance of household level characteristics. For example, an important strand of the literature concerns the 'constraints' faced by, and which effectively define, semi-subsistence rural households: e.g. market imperfections, transactions costs and other frictions (see e.g. Key, Sadoulet and de Janvry 2000). One overwhelming conclusion of this work is that, not only do households face different constraints, the constraints also differ in their severity. Carter and Yao (2002) provide evidence of this in China with regard to land rental markets and credit constraints, Deininger and Jin (2000) study security of property rights, while Bowlus and Sicular (2003), Matsche and Young (2004) and Vakis et al (2004) are concerned with heterogeneity with regard to access to off-farm labour market in China, Zimbabwe and Peru respectively. Grosjean (2005) shows that many of the market imperfections discussed in the theoretical and applied literature are reflected in our data. For example renting land is still prohibited or submitted to authorization in nearly 11% of our surveyed villages, while only 22% of households operate in this market. Furthermore, land rights are perceived to be insecure in some villages and land reallocation by local governments is still expected by certain households.

Such local and household heterogeneity is important for the analyst since the presence,

absence or severity of such constraints has been shown to determine household responses to public interventions. Therefore, one can expect households to respond in heterogeneous ways to interventions such as the SLCP. For example, evidence for heterogeneous impacts of poverty alleviation interventions in China have been noted by Chen and Ravallion (2003), while in Kenya, Evenson and Mwabu (1998) show that the magnitude of the impact of agricultural extension on yields differs across the quantiles of the distribution of yields⁷. The conclusion that one must take from the sum of these contributions is that heterogeneity at the local and household level is the rule rather than the exception. Moreover, given that regions and households are likely to differ in ways which are not observable to the analyst, any econometric approach to the evaluation of the impacts of the SLCP should be sufficiently flexible to account for heterogeneous responses.

Secondly, and following on from this point, is the question of selection into the programme. As described above, our data and all the available evidence from previous studies suggests that the programme is predominantly involuntary with households targeted by local government on the basis of programme objectives: environmental and poverty alleviation, and more arbitrary attributes: e.g. ease of implementation (Xu and Cao 2002). In either case it seems clear that selection is unlikely to be random and will be based upon a number of local and household level characteristics which may or may not be observable to the analyst. As is well known, this presents particular problems for the identification of the impact of the SLCP and so the econometric model needs to control for selection on both heterogeneous observed and unobserved local and household level characteristics.

From the policy perspective however, we are interested in the extent to which the selection of participants, and hence the targeting of the programme has improved the lot of the poor. The question of the effectiveness of targeting for rural poverty alleviation is not new in China and the trade off between direct assistance of the poor at a local level and more coarse regional level programmes has been the subject of much debate (Park et al 2002, Jalan and Ravallion 1998). In our case the questions are: Given the various attributes that influence participation, to what extent has this highly targeted policy targeted poor households; Has the SLCP increased poor participants' incomes compared to non-participants? and; To what extent has the impact been sufficient to lift participant households out of poverty?

⁷Evidence exists for small impacts as a result of large transactions costs (de Janvry and Sadoulet 2002) and responses being the opposite of those intended or expected (OECD 2001).

This immediately gives rise to third question. Against which yardstick should one measure poverty alleviation? The definition of poverty is a subject of much debate in China as well as elsewhere. One important difference exists between the official poverty line in China, which in purchasing power parity (PPP) terms is equal to approximately Y640 per capita per year, and the international yardstick of \$1 per day, or Y900 per capita per year in PPP terms, commonly employed by the international aid agencies. Given the potential for heterogenous impacts we should expect that the impact of the programme on poverty alleviation will vary depending upon the poverty line employed. Indeed, Chen and Ravallion (2003) show that this was the case for the South West China Poverty Reduction Strategy Programme, finding that although the average poverty alleviation impact upon the participant households was insignificant with regard to the poverty line of \$1 per day, when measured against lower poverty lines the impact was much greater and economically and statistically significant. Therefore, if we are interested in measuring the impact of the SLCP upon poverty it makes sense to measure this impact across a wide range of poverty lines.

In short, in order to identify the impact of the programme upon the participants' incomes and income sources and hence, its effect upon poverty alleviation, the following issues needs to be considered: heterogeneity of household responses, selection into the programme on the basis of unobservable household or village level characteristics, and the yardstick against which impacts are measured.

5.4.2 The objectives of the current study

The household survey undertaken for this study has a number of particularly desirable features which mean that we are uniquely placed to deal with the issues identified above. The data available to us and the transformations undertaken for the purpose of analysis are described in greater detail in Section 5.6.1 below. However, for the purpose of outlining the objectives of this study we describe the key features of the data which allow us to overcome some of the inadequacies of previous work in this area.

Firstly, we have collected pre- and post-programme data on participant and non-participant households in the regions in which the SLCP has been implemented. Firstly, our study covers the four year period from 1999 to 2003 and hence we are better placed to analyse the medium to longer term impacts of the programme upon the welfare and structure of farming activity among participant households. Secondly, we have detailed data at the individual level con-

cerning income sources over time allowing a detailed analysis of the impact of the SLCP upon these outcome variables. Thirdly, we have household and village level data on the prices of agricultural production and wages paid off-farm. In addition, the panel nature of the data allows us to control for unobservable time invariant heterogeneity at the household and village level. This in turn allows us to control for non-random selection and make the SLCP mimic a randomised control experiment. Lastly, we have data on local institutions, constraints, and the implementation of the SLCP which allow the participation decision to be precisely modelled. All of these features represent an improvement upon previous work.

The over-arching objective of this Chapter is the analysis of the impact of the SLCP upon the incomes of participant households. Given the preceding discussion the specific objectives are therefore:

1. To evaluate the impact of the programme on household incomes in total and the components thereof (livestock, crops, forest products and off-farm activities) controlling for selection into the programme and allowing for heterogeneous responses.
2. To evaluate the impact of the programme on incomes at different quantiles of the income distribution and hence the impact on the distribution of income.
3. To estimate the extent to which the SLCP has alleviated poverty as measured by several yardsticks.
4. To draw inference from the preceding analyses as to the overall impact of the programme, its impact on poverty alleviation and its sustainability once compensation ceases.
5. To provide guidance for future work.

The analysis that we undertake in what follows is entrenched in the statistical and econometric literature on programme evaluation and in particular the literature concerned with ‘matching’ (e.g. Heckman et al 1997, 1998, Blundell and Costa-Dias 2002, Abadie 2002). Given the discussion concerning the heterogeneity of responses among rural households it is important that the empirical approach caters for the possibility of differential impacts across households. This is something that many of the matching estimators that we propose accommodate in a more comprehensive manner than previous analyses⁸. The following Section describes the pro-

⁸Uchida et al (2004) use a fixed effects logit model which controls for individual time invariant specific effects in a similar manner to the Difference in Differences estimator that we propose.

programme evaluation problem and hence why previous analyses are likely to have produced biased results. The estimators for non-experimental data are then described before moving onto the empirical strategy

5.5 Programme Evaluation Methods

In this Section we describe the general programme evaluation problem and the ideas that have been developed to overcome it. Our outcome measures for the SLCP will be total incomes and the components of income and our aim is to obtain consistent and unbiased estimates of the changes in these outcome measures that are attributable to the SLCP programme. Our parameter of interest is the Average Treatment on the Treated (*ATT*) which is a measure of the impact of the SLCP on the outcome measure for participants compared to the case in which they had been non-participants. In our case we establish the extent to which the SLCP has had an impact in incomes and income sources. To identify *ATT* we must overcome the programme evaluation problem and find conditions under which non-participants can be used as a suitable comparison group for participants. We describe the traditional matching estimator, as it relates to Rubin and Rosenbaum (1983), and the extensions to this estimator that have been proposed more recently (Heckman et al 1997). In particular we focus upon estimators that allow us to exploit the panel structure of our data, namely the matched Difference in Differences estimator. We describe the parametric, non-parametric and semi-parametric variants of this estimator that we ultimately employ.

5.5.1 The program evaluation problem

The programme evaluation problem is effectively a missing data problem. That is, an individual or a household can only be observed in one state at any one time: they are either a participant in a programme or non-participant at time t . If the participation in the programme is denoted by the variable D : $D = 1$ for participants and $D = 0$ for non-participants, and our outcome variables are respectively denoted Y_1 and Y_0 , then at any one time we observe the following data for an individual:

$$Y = DY_1 + (1 - D)Y_0$$

This representation is common in the literature and stems from Roy (1951) through to Quandt

(1972) and Rubin (1978). The usual version of this model is written as a function of observables (to the econometrician) and unobservables, additively in separable form:

$$Y_0 = g_0(X) + U_0 \quad (5.1)$$

$$Y_1 = g_1(X) + U_1 \quad (5.2)$$

where X represents the observable determinants of the outcome variable Y_k for an individual k , $g_i(X)$ is the function which captures this relation when an individual is a participant ($i = 1$) and a non-participant ($i = 0$), and U_i represent the unobservable determinants. The impact for an individual of a policy intervention can be represented by the term $\Delta = Y_1 - Y_0$. Clearly, were Y_1 and Y_0 observed simultaneously for individuals there would be no programme evaluation problem since Δ would be observed for each individual. It is the fact that Y_1 is not observed for non-participants while Y_0 is not observed for participants that the programme evaluation problem exists. That is, counterfactuals are not observed for individuals. For this reason focus is usually placed upon the population and summary statistics for mean impacts (Δ) for individuals with characteristics X . The parameters of interest frequently include:

$$\textbf{Average Treatment on the Treated: } ATT = E(Y_1 - Y_0|X, D = 1) = E(\Delta|X, D = 1) \quad (5.3)$$

$$\textbf{Average Treatment on the Untreated: } ATU = E(Y_1 - Y_0|X, D = 0) = E(\Delta|X, D = 0) \quad (5.4)$$

$$\textbf{Average Treatment Effect: } ATE = E(Y_1 - Y_0|X) = E(\Delta|X) \quad (5.5)$$

Of these parameters it is the former which has perhaps received the most attention. ATT measures the difference between the treatment and non treatment outcome for programme participants, that is, the treatment group. In terms of the separable model of (5.1) and (5.2) ATT can be written:

$$ATT = g_1(X) - g_0(X) + E(U_1 - U_0|D = 1) \quad (5.6)$$

The programme evaluation problem still remains even when cast in this light since estimating ATT requires information on the counterfactual quantity $E(Y_0|D = 1)$ while the observed data only allow the calculation of the following quantities:

$$E(Y_1|X, D = 1) = g_1(X) + E(U_1|X, D = 1) \quad (5.7)$$

$$E(Y_0|X, D = 0) = g_0(X) + E(U_0|X, D = 0) \quad (5.8)$$

One estimator might use observed data to estimate ATT , by taking the difference between 5.7 and 5.8, however this estimator contains selection bias reflecting self-selection into the programme on the basis of unobservable characteristics⁹. To see this consider the decomposition of this estimator:

$$\begin{aligned} E(Y_1|X, D = 1) - E(Y_0|X, D = 0) &= E(Y_1 - Y_0|X, D = 1) + \{E(Y_0|X, D = 1) - E(Y_0|X, D = 0)\} \\ &= ATT + BIAS \end{aligned} \quad (5.9)$$

Here, the last term in braces on the right hand side represents the selection bias. In terms of the separable model above the bias can be written as:

$$BIAS = E(U_0|X, D = 1) - E(U_0|X, D = 0) \quad (5.10)$$

which makes clear the selection on unobservables: as long as $E(U_0|X, D = 1) \neq E(U_0|X, D = 0)$, the bias exists.

Experiments can be designed in order to circumvent this problem through randomisation. By randomly selecting actual participants and non-participants among those who have selected themselves as potential participants an unbiased estimate of ATT can be obtained since for those who selected themselves as potential participants $E(U_0|X, D = 1) = E(U_0|X, D = 0)$ between eventual participants and non-participants.

For non-experimental data a plausible comparison group is not immediately available and the problem of selection bias can remain. Fortunately there exists a number of solutions to

⁹In fact, selection could take place on some other basis, e.g. by the parties implementing the programme such as local authorities. However, provided selection takes place on the basis of variables unobserved to the econometrician the selection bias term remains.

this problem which are commonly applied to non-experimental data. Each of these solutions presents an identification idea that effectively constructs a suitable comparison group from which to estimate the parameter of interest or some averaged version thereof. In what follows we describe a number of the estimators that are relevant to the programme in hand: the SLCP. The discussion takes place with regard to the average treatment on the treated parameter (*ATT*) although the ideas hold analogously for the other parameters such as those presented above.

5.5.2 Estimators for non-experimental data

5.5.2.1 Matching

The idea of matching is highly intuitive and it has been used extensively in the evaluation of social programmes in developed and developing countries alike (see e.g. Heckman et al 1997, Bhandyopadhyay et al 2004). Interestingly, Chen and Ravallion (2003) used a number of matching techniques to evaluate the impact of poverty alleviation strategies in south western China. Estimation of *ATT*, for example, using matching can be thought of as follows.

For each individual, k , in the treatment group a measure of the change in the outcome variable, Δ_k , is constructed e.g. $\Delta_k = Q_{1k} - Q_{0j}$, for each member where individuals from the participant group and individuals from the non-participant group, j , are matched on the basis of the similarity of their observable characteristics. Where the scalars Q_{1k} and Q_{0j} are quantities containing the outcome variables Y_{1k} and Y_{0j} ¹⁰. Of course, there are many ways in which one could determine a suitable match for an individual i , and in reality, rather than matching participants with single non-participants many matching estimators use a weighted average of non-participants' outcomes as the basis of the comparison. Hence, where I_0 and I_1 are indices for non-participants and participants respectively, matching estimators of *ATT* can be generally described as first constructing the following estimate of Δ for each programme participant (Heckman et al 1997):

$$\Delta_k = Q_{1k} - \sum_{j \in I_0} W_{N_0, N_1}(k, j) Q_{0j} \quad (5.11)$$

where $\sum_{j \in I_0} W_{N_0, N_1}(k, j)$ represents the distance measure employed to compare participants

¹⁰For example, the impact could be defined as $\Delta = Y_{1i} - Y_{0j}$. In fact, as we shall see, the measure of individual impact may include adjusted values of these outcome variables.

and non-participants and N_0 and N_1 is the number of non-participants and participants respectively¹¹. The matching estimate for ATT can then be represented as a weighted average of this measure¹²:

$$ATT_{match} = \sum_{k \in I_1} w_{N_0, N_1}(k) \left[Q_{1k} - \sum_{j \in I_0} W_{N_0, N_1}(k, j) Q_{0j} \right] \quad (5.12)$$

where $\sum_{k \in I_1} w_{N_0, N_1}(k)$ is used to select different domains of the variables used to generate the match: the conditioning variables, Z . Different matching methods use different forms of $\sum_{j \in I_0} W_{N_0, N_1}(k, j)$ and $\sum_{k \in I_1} w_{N_0, N_1}(k)$.

The identification idea that underpins this estimator is that by conditioning upon the observable determinants, Z , of the programme participation decision, D selection bias ($BIAS$) is eradicated. In general terms the solution to the programme evaluation problem offered by matching is based upon the following assumption¹³:

$$(Y_1, Y_0) \perp D | Z \quad (A-1)$$

That is, the outcome variables are statistically independent/orthogonal (where orthogonality is represented by \perp) of the conditional participation decision, where Z represents the observable variables upon which the decision is decision is conditioned¹⁴. This independence rules out the selection on unobservables and for this reason this method is frequently referred to as ‘selection on observables’ (Heckman and Robb 1986). This identification assumption solves the selection problem since (A-1) implies that, if the means exist:

$$\begin{aligned} BIAS &= E(Y_0 | X, D = 1, Z) - E(Y_0 | X, D = 0, Z) \\ &\implies E(Y_0 | X, Z) - E(Y_0 | X, Z) = 0 \end{aligned} \quad (5.13)$$

¹¹This is usually a positive valued function and defined such that for each $k \in I_1$, $\sum_{j \in I_0} W_{N_0, N_1}(k, j) = 1$.

¹²Note that matching with a single individual and simply taking the difference in means for participants and non-participants fall out as special cases.

¹³Matching does not require additive separability as describe in the model above. In fact the assumption $(Y_1, Y_0) \perp D | Z$ is the general form of the matching assumption Navarro-Lozano (2004).

¹⁴We make a distinction here, which is useful later on, between the set of observable variables which determine outcomes, X , and the set of observable variables that determine the participation decision, Z . These may or may not coincide.

This means that the missing counterfactual, $E(Y_0|X, D = 1, Z)$, can be estimated by $E(Y_0|X, D = 0, Z)$ to estimate ATT as described in (5.6) above. Effectively, it is assumed that the bias does not exist when conditioning on Z .

It seems intuitive to match like people to like, and that matching upon on a many characteristics would be desirable. However, particularly when dealing with non-parametric estimators, high dimension matching can be a problem for efficiency. Fortunately, Rosenbaum and Rubin (1983) showed that if in addition to (A-1) the following assumption holds:

$$0 \leq P(Z) \leq 1 \quad (A-2)$$

that is, persons with the same characteristics Z can be observed as either participants or non-participants for all values of Z , then:

$$(Y_1, Y_0) \perp D | P(Z) \quad (A-1')$$

and hence matching can take place on the basis of the propensity score, $P(Z)$, alone and ATT can be consistently estimated. To see this note that, given assumption (A-1'): we have both:

$$\Pr(D = 1 | Y_1, Y_0, Z) = \Pr(D = 1 | Z) = P(Z) \quad (5.14)$$

and:

$$\begin{aligned} BIAS &= E(Y_0 | X, D = 1, P(Z)) - E(Y_0 | X, D = 0, P(Z)) \\ &\implies E(Y_0 | X, P(Z)) - E(Y_0 | X, P(Z)) = 0 \end{aligned} \quad (5.15)$$

Hence, the bias in (5.9) disappears and matching among individuals can take place on the one dimensional propensity score $P(Z)$, even though Z may have many components.

The identification conditions for the estimation of ATT are weaker than those outlined above. Since it is only an estimate of the counter-factual mean $E(Y_0 | X, D = 1)$ that is required here, for matching to provide an unbiased estimate of ATT requires only the weaker condition that $Y_0 \perp D | P(Z)$. By a similar logic it is clear that to estimate the average treatment on the untreated, ATU in (5.4), requires only that $Y_1 \perp D | P(Z)$ since the counterfactual mean in this case is $E(Y_1 | X, D = 0)$. Indeed, as Heckman et al (1997) note, under the stronger assumption

of (A-1) all the parameters of interest described so far coincide, whereas under the weaker assumptions they are distinct.

The assumption that $0 \leq P(Z) \leq 1$ effectively assumes that the support of Z is the same for participants as for non-participants. This is a strong assumption and has been shown to be untrue in many cases (Heckman et al 1997). It is usual to condition on the common support of these variables, say S , in order to use matching, that is, only where there is common support of Z is it reasonable to match participants and non-participants. This issue is addressed in the analysis below.

Whether matching takes place on the propensity score or on particular variables alone, individuals are matched to one another on the basis of a predefined distance measure and given that there are a number of distance measures that can be employed there is naturally a discussion to be had regarding which of these measures is likely to be the most efficient in any particular context. Heckman et al (1997) undertake an analysis of the different matching estimators and their associated distance measures and compare the outcomes of these estimators to the results obtained from a randomised control group. That is, they compare the matching estimators for non-experimental data to results for the experimental data that they try to emulate. Similar analyses have been undertaken in the context of China, for example, Chen and Ravallion (2003) and Park et al (2001) employ a number of matching techniques which differ in the distance measure and find that this choice is of some importance for the evaluation of the policy.

In the following Section we turn to an approach nested in the framework above which allows us to exploit the panel nature of the data that we intend to use. Indeed, the Difference in Differences estimator not only exploits the panel data but it also allows for a more flexible underlying behavioural model of economic choices than that of the pure matching model. In this light we introduce the 3 estimators of the parameter of interest, the average treatment on the treated (*ATT*). The first is the fully parametric estimate of treatment effects that appears in Ashenfelter and Card (1985), the second is the non-parametric estimator of Heckman et al (1997) and the third is the semi-parametric approach recently described by Abadie (2005).

5.5.2.2 Difference in differences estimators (*DID*)

Linear *DID*: The linear Difference in Differences estimator is one of the most common methods of evaluating the impact of a programme on relevant outcome variables. The *DID*

estimator makes use of panel data, that is, pre- and post-programme data are required for the participants and non-participants, and hence we observe the participants switching from an untreated state to a treated state. Even in the presence of panel data, however, the outcome variables in any time t , $Y_0(t)$ and $Y_1(t)$, are not observed for any one individual, and the programme evaluation problem remains. The presence of panel data allows an alternative solution to the programme evaluation problem and associated selection issues¹⁵.

Abadie (2005) provides a succinct explanation of the *DID* estimator based on the formulation of Ashenfelter and Card (1985), which we draw from here¹⁶. Letting $Y_k(t)$ be the outcome for individual k , where for the pre-treatment period in period $t = 0$ and for the post-treatment period $t = 1$. As before the dummy variable $D_k(t) = 1$ for the treated population and $D_k(t) = 0$ for the untreated, hence $D_k(1) = 1$ for the treated and $D_k(1) = 0$ for the comparison group¹⁷. Assuming separability as in equations (5.1) and (5.2) above, suppose that the outcome variable is determined by the familiar components of variance model:

$$Y_{kt} = \alpha.D_k(t) + (\phi_k + \theta(t) + \varepsilon_k(t)) \quad (5.16)$$

where the error term has been decomposed into three unobservable components: an individual specific component, ϕ_k , a common (macro) time specific component, $\theta(t)$, and an individual specific mean zero temporary component $\varepsilon_k(t)$: $U_k(t) = \phi_k + \theta(t) + \varepsilon_k(t)$. In this parametric formulation, the parameter α represents the impact of the programme on the outcome variable. In this simple form this treatment is common across all treated individuals and not determined by observable characteristics X , that is, this model does not account for heterogeneous impacts. As in the usual error components model, the parameter of interest is not identified without further restrictions. Abadie shows that a sufficient condition for this is that selection for treatment does not depend upon the individual transitory shocks. $\varepsilon_k(t)$, that is, $P(D_k(1) = 1 | \varepsilon_k(t)) = P(D_k(1) = 1)$, and that this assumption implies that $E[(1, D_k(1), t, D_k(t)) * \varepsilon_k(t)] = 0$. This allows the parameters of the following representation to be identified by ordinary least squares¹⁸:

¹⁵Heckman and Robb (1995) show that strict panel data is not always required and that repeated cross-sectional data can solve the programme evaluation problem equally well in many instances.

¹⁶Intuitive explanations can also be found in Blundell and Costa-Dias (2002) for example.

¹⁷Of course, $D_k(0) = 0$ for all parties.

¹⁸Where $v_k(t) = \phi_k - E[\phi_k | D_k(1)] + \varepsilon_k(t)$, $\delta = \delta(1) - \delta(0)$, $\mu = E[\phi_k | D_k(1) = 0] + \delta(0)$, and $\tau = E[\phi_k | D_k(1) = 1] - E[\phi_k | D_k(1) = 0]$. Note also that $E[\phi_k | D_k(1)] = E[\phi_k | D_k(1) = 0] +$

$$Y_k(t) = \mu + \tau.D_k(1) + \delta.t + \alpha.D_k(t) + v_k(t) \quad (5.17)$$

The *DID* estimator is so called because under the identifying assumption:

$$\alpha = \{E[Y_k(1)|D_k(1) = 1] - E[Y_k(1)|D_k(1) = 0]\} - \{E[Y_k(0)|D_k(1) = 1] - E[Y_k(0)|D_k(1) = 0]\} \quad (5.18)$$

and OLS provides the sample counterpart to this parameter.

This parametric approach to the estimation of *ATT* provides us with a starting point for the estimation of the impact of the SLCP upon various outcome variables in China. Indeed, where panel data is available the parameter can be estimated either by a simple t-test of mean differences between treatment and control groups or by simple OLS regression of $Y_k(1) - Y_k(0)$ on a constant and $D_k(1)$. In fact this approach allows us to see the implication of the identifying assumption since the OLS regression yields:

$$\begin{aligned} ATT_{DID} &= \alpha \\ &= \{E[Y_k(1) - Y_k(0)|D_k(1) = 1] - E[Y_k(1) - Y_k(0)|D_k(1) = 0]\} \\ &\quad + E[\varepsilon_k(1) - \varepsilon_k(0)|D = 1] - E[\varepsilon_k(1) - \varepsilon_k(0)|D = 0] \end{aligned} \quad (5.19)$$

The *DID* estimator therefore assumes that the trend in $\varepsilon_k(t)$ for non-participants is the same for participants had they not been participants, that is:

$$E[\varepsilon_k(1) - \varepsilon_k(0)|D = 1] = E[\varepsilon_k(1) - \varepsilon_k(0)|D = 0] \quad (A-3)$$

The *DID* estimator has been explained thus far in the absence of additional covariates, X , upon all or part of which the participation decision and the outcome variables may depend. More importantly, given the identification assumption for ATT_{DID} , these covariates may also control for heterogeneous outcome dynamics (Abadie 2005). Covariates are commonly incorporated linearly (Ashenfelter and Card 1985):

$$Y_k(t) = \mu + X'_k \pi(t) + \tau.D_k(1) + \delta.t + \alpha.D_k(t) + v_k(t) \quad (5.20)$$

$$[E[\phi_k|D_k(1) = 1] - E[\phi_k|D_k(1) = 0] - E[\phi_k|D_k(1) = 0]].D_k(1).$$

where the coefficients on X change over time and X_k must be uncorrelated with $v_k(t)$. To reiterate, cast in this form the treatment effect, α , is modelled as being constant across all individuals. By generating a number of interaction effects it is possible to estimate how the impact of the programme varies over different values of X : e.g. by gender of region. It should also be clear that the *DID* estimator allows for selection on unobservables reflected in ϕ_k which was disallowed under conditional independence assumption of the simple matching procedure. That is, a wider variety of behavioural models are compatible with the *DID* estimator, including selection on expected returns.

The parametric approach described thus far is useful to the extent to which it allows the identification of the parameters of interest and predictions to be made out of sample. In effect the parametric approach represents another form of matching in which parametric assumptions have been substituted for the matching criteria described above. In this way the treatment and comparison groups are made comparable. However, these assumptions are not innocuous and may introduce bias where the parametric approximation is weak and significant heterogeneity exists in the impact of the programme. In general non-parametric estimators are desirable in the *DID* framework.

Non-/semi-parametric Matching *DID* estimators: Heckman et al (1998): Heckman et al (1997) generate a number of extensions which combine matching and *DID* techniques. The advantage of these extensions is that they combine the desirable features of each estimator. For example, the simple matching approach described above does not conform to conventional economic models of selection in which selection takes place on the basis of unobservables and yet matching is not without some intuitive appeal. However, the *DID* approach does allow selection to take place on unobservables in the form of ϕ_k and θ_t : the individual and time specific effects. By combining the two it is possible to cater for more realistic economic models of programme selection whilst maintaining the intuitive appeal of the matching idea in controlling for selection on observables.

Heckman et al (1997) show that their matching *DID* estimator can be written in terms of (5.11) and (5.12) by simply assuming $Q_{1k} = (Y_{1kt} - Y_{0kt'})$ and $Q_{0j} = (Y_{0jt} - Y_{0jt'})$. In fact the equivalence extends further since the *DID* estimator can be written in terms of the simple single period matching estimator. That is:

$$ATT_{DID} = ATT_{match,t} - ATT_{match,t'} \quad (5.21)$$

Furthermore, Heckman et al (1997) show how the efficiency of the matching approach can be enhanced by exploiting the separability assumptions commonly employed in econometrics, as exhibited for example in (5.16), and exclusion restrictions on the selection and outcome equations, that is exploiting the fact that the variables which determine outcomes are not necessarily the same as those that determine programme participation. The latter is highly relevant where panel data is concerned. This leads to the regression corrected matching *DID* estimator in which $Q_{1k} = \left((Y_{1kt} - X_{kt}\hat{\beta}_0) - (Y_{0kt'} - X_{kt'}\hat{\beta}_0) \right)$ and $Q_{0j} = \left((Y_{0jt} - X_{jt}\hat{\beta}_0) - (Y_{0jt'} - X_{jt'}\hat{\beta}_0) \right)$ for participants k and non participants j . $\hat{\beta}_0$ is a parameter vector estimated on non-participant data (see Appendix 1 for details). Each of these adjustments have been successful in reducing bias in the evaluation of employment training schemes and other policy interventions and we employ these methods in addition to those mentioned above for comparative purposes¹⁹. The identification conditions for this estimator are similar to those for the simple matching estimator described in (A-1) and (A-1') above, however, the conditional independence condition now relates to the residuals of the regression on the outcome variable rather than the levels themselves (See Heckman et al 1998, p268).

The Abadie estimator (Abadie 2005) Abadie (2005) proposes a semi-parametric *DID* estimator which incorporates covariates in a manner related to Heckman et al (1998a) and Ashenfelter and Card (1985). The role of the covariates in Abadie (2005) is similar to that of Ashenfelter and Card (1985) in that they serve two important roles for the *DID* estimator, aside from allowing the separation of the determinants of outcome and participation. Firstly, the presence of covariates can allow the estimate of the parameter of interest (e.g. *ATT*) to differ among individuals, or more usually groups of individuals. In the parametric case of Ashenfelter and Card this could be achieved by generating interaction terms with the desired components of T with the variable representing participation. In the non-parametric case a certain amount of integration will be required across the desired components of T . Secondly, and more importantly with regard to the identification condition of the *DID* estimator, conditioning on the

¹⁹For example, Glick et al (2004) use the regression adjusted methods to evaluate the impact of capital account liberalisation on the prevalence of currency crises. Navarro-Lozano (2003) employs this technique in the evaluation of training schemes in Mexico.

covariates can extend the identification conditions for the *DID* estimator to situations in which differences between the treatment and non-treatment groups cause differences in the dynamics of the outcome variables. Provided these differences are the result of observed characteristics, conditioning on these characteristics means that the usual identification condition (assumption A-3) above becomes a conditional identification condition²⁰. That is by conditioning on variable measuring the observed differences, say x , the conditional participation decision remains independent of the individual transitory shocks, that is:

$$P(D_k(1) = 1|x, \varepsilon_k(t)) = P(D_k(1) = 1|x) \quad (5.22)$$

and assumption A-3 still holds. Under these conditions it remains possible to retrieve the parameter of interest using the *DID* estimator (Abadie 2005).

Abadie (2005) proposes a simple estimator for *ATT* of both conditional regression adjusted and unconditional forms. The estimator is simple compared to the matching *DID* estimator of, e.g., Heckman et al (1998a) since it is based purely upon the differences in the outcome variable across time for individuals for participants and non-participants, that is, $\Delta = Y_k(1) - Y_k(0)$, and although the propensity score must be estimated there is no need to engage in the matching procedure in the generation of the counter-factual comparison group for each participant. The estimator generates a weighted average of the differences across time for each individual where the weights are a function of the propensity score. In short, the unconditional *DID* estimator of *ATT* described by Abadie (2005) can be written as:

$$ATT_{DID}^A = E[Y_1(1) - Y_0(1) | D = 1] = E\left[\frac{Y(1) - Y(0)}{P(D = 1)} \cdot \frac{D - P(D = 1|X)}{1 - P(D = 1|X)}\right]$$

As Abadie (2005) notes, this estimator works by weighting down values of Δ for the non-participant group which for those values of the covariates which are over-represented in the

²⁰The classic example of such a case is that of ‘Ashenfelter’s dip’ (Ashenfelter 1978), which describes the observation that participants to the programme suffer a momentary reduction in income in the period immediately prior to becoming participants. This fact immediately sets the participant group apart from the non-participant group by implying that participation occurs if pre-programme income falls below some threshold. Such a case means that the equality of trends implied by the identification condition of the *DID* estimator will no longer hold. By conditioning upon income prior to participation, however, a conditional version of the *DID* identification condition will hold and the *DID* estimate of the programme impact will remain unbiased (Ashenfelter and Card 1985, Abadie 2005).

among this group, and weighting up the values of Δ which are under represented²¹. The implementation of this estimator is a simple two step procedure first requiring the estimation of the propensity score and then the use of the predicted values to calculate the sample analogue. This procedure, along with the conditional version is described in greater detail in Appendix 1. Although the identification is obtained non-parametrically the various steps of the estimator can be undertaken parametrically. This is particularly useful where one has small datasets and where high dimensional non-parametric estimators become difficult to interpret and more importantly, inefficient²². Note that in this case regression adjustment takes place via a regression on the differences, and so time invariant and time varying parameters can be used in principle.

5.5.2.3 The relative merits of the estimators and procedures

In Section 5.3 the structure of the SLCP was discussed and the manner in which households and plots are selected into the programme. as the discussion of the estimators above makes clear, the nature of participation decision is a crucial element of the identification assumptions. For example, the simple matching estimator presented in Section 5.5.2.1 relies entirely upon the assumption that selection into the programme is based upon characteristics that are observable both to the individual and analyst. Of course this precludes self-selection into a programme on the basis of unobservables, represented by U_0 and U_1 in the foregoing separable example, and hence it is inconsistent with the behavioural models commonly employed by economists to analyse such decisions²³. In short the matching model is relevant when selection into the programme is based on observable characteristics only and therefore would be useful estimator

²¹Over-representation is reflected by low values of $P(D = 1|Z)/P(D = 0|Z)$ and vice versa.

²²Abadie (2005) also explains succinctly how the inclusion of additional regressors can account for differences in the dynamics of the outcome variables for participants and non-participants which could invalidate the identification assumptions for the *DID* estimator.

²³Navarro-Lozano (2004) provides a simple exposition of this point in the context of the Roy (1951) model. Consider the Roy model described in (5.2) and (5.1) above. In this where the participation decision is made by individuals based on the expected monetary gain, that is:

$$\begin{aligned} D &= 1(Y_1 - Y_0 - C), \\ &= 1(g_1(X) - g_0(X) - C + U_1 - U_0) \end{aligned}$$

where $1(\cdot)$ is an indicator function and C is the cost of participation. In this case the selection into the programme takes place on the unobservable gain $(U_1 - U_0)$ which is ruled out by matching.

in the event that programme participants are not self-selected but participate by diktat from the implementing agency, and the agency selected on the basis of characteristics observable by the analyst.

The matching *DID* estimator, however, supports broader and perhaps more realistic models of economic behaviour in programme selection. For example, if we think in terms of the familiar components of variance model shown in equation (5.16) above and we think of the outcome variable as income, the time invariant individual or household specific component, ϕ_i can be thought of as representing the permanent component of household income. This individual component is swept out when differences are taken. Given the conditional independence assumption that is required for the matching *DID* estimator to be consistent participation can take place on the basis of this unobservable individual specific component. For example, the following participation rule would be eligible:

$$D_t = \begin{cases} 1 & \text{if } \phi_k < \bar{Y} \\ 0 & \text{otherwise} \end{cases}$$

where \bar{Y} could represent some an individual valuation of the expected benefits of programme participation and may reflect individual preferences such as discount rates, preferences for programme participation.

In the case of the SLCP the perceived ability to find alternative income sources will be reflected here. Indeed, Grosjean (2005) posits that the impact of the programme may be to relax previously binding constraints, hence enabling a permanent release from poverty. Again, this behaviour could be captured here. Since the conditional independence rule refers only to the individual transitory component, $\varepsilon_k(t)$, selection into the programme of this nature is acceptable in the *DID* approach²⁴.

Similarly, these arguments could be couched at the village or district level. This means that the *DID* estimator can control for village level unobservables and therefore certain types of associated bias. For example, Heckman and Robb (1995) show that certain *DID* estimators can also be robust to choice based sampling and contamination bias. Choice based sampling bias results when the probability of sampling an individual or household does not reflect the population probability that the household is a participant. This would be the case in the model

²⁴ Ashenfelter and Card (1985) provide some analysis of the empirical implications of selection rules and the structure of the outcome equation in this light.

in equation (5.16) where the usual conditional independence assumptions hold for differenced error components. Hence, where longitudinal data is available the analysis of treatment effects becomes subject to less restrictive behavioural assumptions and importantly, can control for time invariant local and individual heterogeneity.

The relative merits of parametric and non-parametric approaches to estimation are well known (see e.g. Härdle 1990, Greene 1998). Convergence of fully non-parametric estimators is dependent upon sample size, kernel choice, bandwidth and the number of regressors and is not generally \sqrt{n} . High dimensional non-parametric regression will require large datasets in order estimates to be accurate, while the results become difficult to interpret with dimensionality greater than two since 4 dimensional pictures would be required. Furthermore, the choice of bandwidth and the weighting functions represents a relatively arbitrary decision. Non-parametric estimators have the benefit of flexibility in the representation of functional forms without resort to parametric assumptions. In the case of matching they also easily accommodate the heterogeneous treatment effects that we have argued will prevail. These benefits are important for programme evaluation and it is against these benefits that the difficulties and the arbitrariness need to be traded off. Semi parametric approaches reflect this trade off by combining non-parametric and parametric components and frequently achieving \sqrt{n} convergence.

Our dataset is relatively small and hence in the work that follows we present and contrast the results of non-parametric, semi-parametric and parametric estimators of the average treatment on the treated. As we describe below, we use the matching *DID* approach in our analysis of the average treatment on the treated and analyse a number of different outcome variables in this framework. We also provide a specific behavioural model for participation in the SLCP which reflects the available evidence on this issue.

5.6 Empirical Strategy

In this Section we describe precisely how we go about achieving the objectives 1-5 of our study. The empirical strategy is as follows.

1. We model the participation decision, estimate the propensity score and analyse the participation decision.
2. Using these estimates we estimate the average treatment on the treated (*ATT*) for measures of total income and the components of income using three estimators. We use a

number of strategies in order to ensure that the choice of estimator does not determine the outcomes. In each case we argue that sample selection is accommodated and in the latter two cases heterogeneity in the impact measure is accommodated. The three estimators are:

- a) the simple unmatched *DID* estimator
 - b) the matched *DID* estimator of Heckman et al (1998)
 - c) the semi-parametric efficient estimator of Abadie (2005).
3. We use unconditional and regression adjusted approaches in each case since regression adjustment has been shown to reduce bias²⁵.
 4. We estimate the impact of the SLCP on the quantiles of the distribution of income. That is we estimate Quantile Treatment Effects (*QTE*) in net income using two methods
 - a) a simple *DID* approach
 - b) a matched *DID* approach using the empirical distribution of participants incomes and the counterfactual values estimated in the matched *DID* approach previously.
 5. Using the empirical distribution of net incomes we use matched and unmatched *DID* methods to evaluate the impact of the SLCP on poverty alleviation for a range of poverty lines.

In this Section we describe the data and analyse the participation decision in the SLCP. In the following Section we show and discuss the results of the estimations of *ATT*. In Section 5.8 we look at the *QTE* and the impact on poverty alleviation.

5.6.1 Data

The SLCP survey was implemented in July and August of 2004 by a survey team from Beijing University. The same two regions were selected as those studied in previous work by Uchida et al (2004): Ningxia and Guizhou provinces, although alternative villages were selected. These surveys came on the back of a piloting exercise in June 2004 undertaken in Zhangbei county, Hebei province. In Guizhou province 12 townships and 21 villages were selected for survey and 131

²⁵Appendix 1 describes the estimation procedure of the semi-parametric regression adjusted procedure of Heckman et al (1997) and that of Abadie (2005).

households consisting of participants and non-participants were surveyed. In Ningxia, 15 townships and 23 villages were selected, and 155 households were interviewed. In tandem with the household surveys 40 village questionnaires were undertaken, 23 in Guizhou and 17 in Ningxia. Additional secondary data was also obtained from the local Forestry Bureaux. Households were selected at random within the villages among participants and non-participants.

The survey elicited responses from households for individual and household level characteristics and contained 4 Sections. Section A contained household level characteristics: family size, land and capital endowments, and individual characteristics: education, age, sex and labour allocation. Section B obtained production level data for the pre and post programme periods. Virtually all participants joined the programme in 2000, and this is the 'pre-programme' year for both participants and non-participants. Plot level data on crop, forestry and livestock outputs and prices were obtained, for both sold and consumed output. In addition individual level data concerning the off-farm labour supply and earnings for each individual in the household was obtained for the pre- and post programme period. Section C focussed solely upon the participants in the SLCP and obtained qualitative responses with regard to their perceptions of the programme, their future intentions and the manner in which the SLCP had been implemented while Section D contained the choice experiment. Section C and D are the focus of other research (Grosjean 2005). In addition a village level survey was undertaken.

Once the data had been entered a number of changes were made in preparation for the analysis. Income variables were generated using price and quantity data provided by households for each agricultural product. Input costs were also used to generate net-income measures. Many households produced crops for own consumption and in that case the value of production was imputed using market prices, as is common practice in such cases (Deaton 2000, Capeau and Dercon 1998)²⁶. A number of manipulations were undertaken in this regard in order to deal with missing data. These are explained in more detail in Appendix 2. All prices and values were expressed in 2002 terms. Village level data from the village leader survey was also attached to the main dataset. This provided details regarding the implementation of the programme, local infrastructure and the level and types of subsidies provided under the SLCP. A monetary value of compensation was calculated which meant adding a value of grain based on local prices, to the monetary component.

Tables 5.1 and 5.2 show some important attributes of the households in each region in

²⁶Even where households were autarkic in certain crops, they were able to reveal market prices for their crops.

Guizhou Household characteristics	Non-participants		Participants	
Personal	mean	sd	mean	sd
Family size	4.82	1.31	4.63	1.57
Education	1.13	0.39	1.32	0.54
Ethnicity (%)	73.20	0.44	85.67	0.35
Off-farm participation (%)	50.00	0.51	58.33	0.50
Agricultural characteristics				
Land endowment (mu)	4.49	4.38	7.60	4.76
Cultivated land (mu)	3.93	2.63	2.86	2.71
Land rented in (mu)	0.58	1.25	0.74	2.60
Land rented in (%)	20.88	0.41	19.79	0.40
Land rented out (mu)	0.0	0.0	0.10	0.54
Land rented out (%)	0.0	0.0	0.05	0.22
Agricultural capital (Yuan)	1380.23	5376.91	260.20	1077.68
Livestock (Head)	9.14	13.55	7.82	10.62

Table 5.1: Guizhou: Descriptive statistics pre-programme

Ningxia Household characteristics	Non-participants		Participants	
Personal	mean	sd	mean	sd
Family size	5.0	1.49	5.41	1.76
Education	1.05	0.39	1.37	0.45
Ethnicity (%)	65.71	0.48	63.33	0.48
Off-farm participation (%)	62.85	0.49	60.00	0.49
Agricultural characteristics				
Land endowment (mu)	18.12	10.79	25.94	19.16
Cultivated land (mu)	16.78	11.29	10.66	8.28
Land rented in (mu)	0.60	2.34	1.09	2.87
Land rented in (%)	11.42	0.32	19.16	0.39
Land rented out (mu)	1.14	2.78	0.22	1.69
Land rented out (%)	17.14	0.38	4.16	0.20
Agricultural capital (Yuan)	2665.85	4845.53	1304.54	2179.81
Livestock (Head)	5.28	6.64	7.33	10.17

Table 5.2: Ningxia: Descriptive statistics pre-SLCP

the pre-programme period and how these differ across participants and non-participants in the SLCP. On the whole the regions are rather similar although households in Guizhou have on average a less valuable stock of agricultural machinery, smaller families and lower land endowments. Some of these attributes are linked of course and stem from the higher population density in Guizhou, one of the underlying reasons for the smaller land endowments. Activity in the land rental market is minimal and somewhat similar in each region, as is average education: A value of 1 represents primary education, while a zero represents no education. Household participation in the off-farm labour market is rather similar in each regional sample. These data fit with the expectations for these regions.

There are some noticeable differences between participants and non-participants. Participants appear to be more educated, with lower agricultural capital and fractionally larger land endowments. In Guizhou participants are more likely to be of Han ethnicity. The differences are not stark however. In determining the impact of the programme upon the participants these compositional differences will be important.

5.6.2 Participation in the SLCP

5.6.2.1 The participation decision: Who decides?

Above we described some of the confusion surrounding the participation in the SLCP. In principle participation in the SLCP is voluntary, suggesting that participants in the programme are self-selected. However, there is anecdotal evidence (CCICED 2002, Xu and Cao 2002, Uchida et al 2004) that the autonomy of individual households is less than complete and that participation in the programme is determined largely by the implementing agency, sometimes to the extent of being completely involuntary (CCICED 2002, Gong and Xu 2002). Indeed, not only has participation and the selection of plots frequently been involuntary, often the nature of the reforestation, e.g. the types of trees planted, has also been at the discretion of the local government. For example, Uchida et al (2004) find that in many cases the compensation for the set-aside land did not cover the opportunity cost and hence it seems unlikely that self-selection by households into the SLCP would take place in such circumstances. This is also suggestive of involuntary participation in the programme²⁷. As a result, Uchida et al (2002) model the

²⁷Of course, there are certain caveats to this intuition based not only upon the unreliable estimates of opportunity cost provided by Uchida et al in the absence of local price data. In addition it could be expected return from participation is increased despite the low imputed value of the subsidy. Grosjean (2005) suggests that the

selection of plots as being at the discretion of the implementing agency.

The village survey undertaken in this study sheds some light on this issue. One of the questions asked was whether or not participation in the SLCP was voluntary and out of 40 village leader surveys undertaken, (covering our sample of 286 households) only 3 village leaders stated that participation in the SLCP was voluntary (representing 21 households). In the majority of cases, 25 villages (143 households), participation was deemed involuntary and entirely at the discretion of the local government and in 12 villages (100 households) selection involved a combination self-selection by households and final selection by the local government implementing agency. In short it is clear that the selection into the program was largely at the discretion of the implementing agency, albeit in about 40% of households from a self selected pool. Selection of plots was on the basis of a number of criteria: slope, degradation, ease of administration and monitoring. These findings are in line with previous findings by Xu and Cao (2002) who questioned the targeting of the SLCP sites by the local government and discovered that contiguity, proximity to roads and selection criteria other than slope were frequently used, contrary to the aims and objectives of the SLCP.

In reality therefore, there are multiple participation rules being employed in the SLCP. In many cases the situation appears to be as described by Uchida et al (2004), however there is a significant minority of cases in which the local government chooses from a self-selected group. The modelling of this process is of importance for two reasons. Firstly, establishing the important determinants of household selection allows us to analyse the extent to which the local governments are targeting in accordance with the objectives of the SLCP. Secondly, the estimation of the participation decision provides the basis for propensity score, the values of which will be used to correct for sample selection bias in the estimation of the impact of the SLCP (Smith and Heckman 2003).

5.6.2.2 The behavioural model of participation in SLCP

As described in Section 5.5.2.1 above, the identification assumption of the simple matching estimator relies upon the fact that selection is based upon observables only. Selection upon unobservables is ruled out and consequently so are many models of economic behaviour, such as the Roy model. However, as described above, the presence of longitudinal data, and the use of the matching *DID* estimator allows a broader array of behavioural models, including selection compensation might release households from previously binding constraints.

on the basis of expected returns from the programme, and the observable and unobservable household determinants of this. It therefore makes sense to present a behavioural model for the participation decision in the context of a matching estimator (see e.g. Ashenfelter and Card 1985, Heckman et al 1997, 1998). Furthermore, Heckman et al (1997) and Smith and Heckman (2003) make clear that in estimating the propensity score it is important from the perspective of efficiency and consistency of the estimators to define the selection process as accurately as possible. In this Section we do this for the SLCP, drawing upon the discussion about the implementation of the programme and the household survey data.

The discussion above made clear that a multiple participation rule approach is required to reflect the decisions of the parties involved (Heckman and Robb 1995, Smith and Heckman 2003). We model the participation in the SLCP as a three stage process involving local government and households. In this framework three decisions are taken: 1) the local government decides whether or not the programme is to be implemented on a voluntary basis or not; 2) Households select whether or not they wish to participate in the programme (where participation is involuntary this stage simply reflects their desire rather than the outcome); 3) the local government chooses the participants (where participation is voluntary the local government chooses among self-selected households, otherwise an unconditional choice takes place)²⁸. Figure 5.1 depicts the decision tree for this process.

We assume that the decision over whether participation will be voluntary or not depends upon the features of the village in which the decision takes place as well as the district within which the village lies. These village and district level characteristics are captured by L . Local governments are assumed to maximise environmental benefits minus the opportunity costs of lost agricultural production as in Uchida et al (2004). We assume that households select themselves for the SLCP on the basis of their expected returns. Following Heckman and Robb (1995) and Blundell and Costa-Dias (2002) this participation decision can be thought of in terms of the following parameterisation for household k with characteristics X , in a village with characteristics L :

$$SS_k = f(X, L) + V_k \quad (5.23)$$

where $f(X, L)$ represents the expected net benefit of participation for the decision maker, k ,

²⁸Notice that we have grouped the 3 villages in which participation was assumed to be purely voluntary with those households for whom participation depends on self-selection and local government decisions.

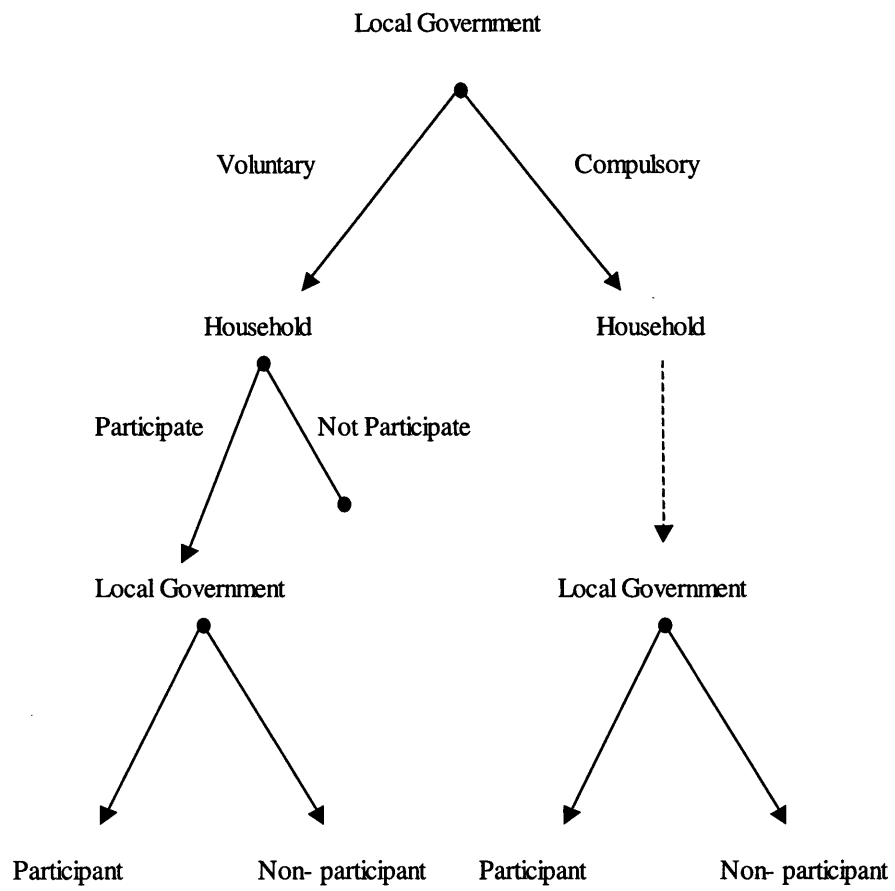


Figure 5.1: Decision tree for participation in the SLCP

and V_k represents the unobservable components of the decision. In this mould $D_k = 1$ if $SS_k > 0$ and $D_k = 0$ otherwise. We model the last step of the participation decision in a manner similar to Uchida et al (2004) and assume that the local government selects household on the basis of a number of local and household characteristics, conditional upon whether implementation is voluntary or not, and in the voluntary case at least, conditional upon self-selection of households.

To understand how we perceive the 3 steps of the participation procedure to fit together it is illustrative to look at the conditional probabilities of participation for a household with characteristics X given the decisions made by the local government with characteristics L . Participation depends upon each of the following probabilities:

Probability of Voluntary Participation Implementation ($V = 1 = \text{voluntary}$):

$$\Pr(V = 1|L) \quad (5.24)$$

Probability of Consideration by Local Government ($SS = 1 = \text{self selection}$):

$$\begin{aligned} & \Pr(SS = 1|V = 1, X, L) + \Pr(V = 0|SS = 1, X, L) + \Pr(V = 0|SS = 0, X, L) \\ &= \Pr(SS = 1|V = 1, X, L) + \Pr(V = 0|L) \end{aligned} \quad (5.25)$$

Probability of Selection by Local Government ($LG = 1 = \text{local government selects}$):

$$\begin{aligned} & \Pr(LG = 1|V = 1, SS = 1, X, L) + \Pr(LG = 1|SS = 1, V = 0,) + \Pr(LG = 1|V = 0, SS = 0) \\ &= \Pr(LG = 1|V = 1, SS = 1, X, L) + \Pr(LG = 1|V = 0) \end{aligned} \quad (5.26)$$

The probability of voluntary participation is simple enough to understand, and this is conditioned solely upon the characteristics of the village and district: L . The probability of consideration by local government represents the probability of remaining eligible for participation once self selection has taken place. This probability is conditioned upon the characteristics of the individual and the decision upon whether or not participation is to be voluntary. It should be noted that if the participation is involuntary then self-selection has no effect upon the probability of participating, hence the presence of $\Pr(V = 0, L)$ in (5.25). The last step is the probability of selection by the local government given involuntary implementation and

voluntary implementation with self-selected households. This model of participation yields the following *ex ante* probabilities for participation in the SLCP:

Probability of Participation:

$$\begin{aligned}
 & \Pr(Par = 1|X, L) \\
 = & \Pr(LG = 1|SS = 1, V = 1, X, L) * \Pr(SS = 1|V = 1, X, L) * \Pr(V = 1|L) \\
 & + \Pr(LG = 1|V = 0, L) * \Pr(V = 0|L)
 \end{aligned} \tag{5.27}$$

Probability of Non-participation:

$$\begin{aligned}
 & \Pr(Par = 0|X, L) \\
 = & \Pr(LG = 0|SS = 1, V = 1, X, L) * \Pr(SS = 1|V = 1, X, L) * \Pr(V = 1|X) \\
 & + \Pr(SS = 0|V = 1, X, L) * \Pr(V = 1|L) \\
 & + \Pr(LG = 0|V = 0, L) * \Pr(V = 0|L)
 \end{aligned} \tag{5.28}$$

A detailed understanding of the participation decision by could be obtained by analysing each individual step. For example, Heckman and Smith (2003) analyse participation in employment training schemes by estimating each of the 5 component probabilities of this participation process. Unfortunately we only have observable data on the first and last decisions in this model and subsequently undertake the analysis for the these steps only. That is, we do not have data with regard to individuals self-selection into the programme. Due to paucity of data we estimate the participation decision in one step recognising that combining these three decisions means that the estimated coefficients represent only the net effect of each explanatory variable on participation²⁹. The effect on each component step remains unidentified³⁰.

²⁹We could estimate a model for the probability of implementation being voluntary followed by a model of the participation of the voluntary and involuntary subsamples to estimate the conditional probabilities in each case. The latter yields an estimate of the probability that the local government chooses a self selected household: $\Pr(LG = 1|SS = 1, V = 1, X, L) * \Pr(SS = 1|V = 1, X, L)$, and the probability that local government selects a household under involuntary implementation: $\Pr(LG = 1|V = 0, L, X)$. When multiplied by the probabilities estimated in the first step this would yield an estimate of the probability of participation for each implementation regime.

³⁰Heckman and Smith (2003) encounter similar problems in their analysis.

5.6.2.3 Estimating the propensity score

Following the justification above, we estimate the participation decision using a probit model on the entire sample, controlling for the village level and household variables X and L , including whether implementation was voluntary or not. Combining the three decision rules into estimation one allows a simple estimation of the propensity score. From this we can also gauge the extent to which the implementing agency for the SLCP is achieving the objectives of the SLCP in the selection of households, that is, the efficient targeting of sloped land and poverty alleviation (Uchida et al 2004). The results of our estimation are shown in Table 5.3 and discussed below³¹.

These results show that the households with lower average productivity (*Agprod*) are selected by local governments. This is shown by the statistically significant coefficient on the average productivity of the household's cultivated land. This variable is the best proxy that we have for the slope of the plots selected since this information was not gathered for all plots. The positive coefficient on per capita income suggests that higher income households are more likely to be selected for the SLCP, although the coefficient is only significant at the 10% level. Also, the positive and significant coefficient on land per capita suggests that households with larger endowments of land per household member are more likely participants. Family size (*Famsize*), the average age of the household (*Agehse*), and Ethnicity have do not have a significant impact upon participation.

With regard to the variables which reflect the characteristics of households able to self select into the programme, that is the interaction effects each with the prefix '*Vol*', higher educated households (*Voled*) with no children under 5 years of age (*Volkids*), with lower levels of agricultural capital (*VolCap*) have a higher probability of participating in the programme other things remaining equal. The latter could be interpreted as a measure of measure of wealth among agricultural households. As explained above these coefficients reflect the net effect of each of the stages of the decision process in Figure 5.1 above, but describe some of the observable features of self selection by households. The sign on the income interaction term is negative suggesting that poor households are again more likely to be participants if they are allowed to volunteer. Overall, however, the results suggest that poor households are not specifically targeted by the SLCP although lower productivity land is being targeted.

³¹Here and henceforth, ^, * and ** mean statistical significance at the 10, 5 and 1% levels respectively.

Variables	Coefficients	z-value
Village level		
Hezhang	-0.266	0.62
Pengyang	-1.143*	2.39
Weining	-0.089	0.20
Yuanzhou	-0.019	0.05
Jingyuan and Zhijin	Reference value	
Voluntary	-0.055	0.08
Household level		
Inpc (Y '000s)	0.12 [^]	1.71
Volinc (Y '000s)	-0.10	0.97
Agprod (Y '000s/ <i>mu</i>)	-1.00**	2.51
VolAg (Y '000s/ <i>mu</i>)	0.67	0.84
Famsize	-0.020	0.22
Volfam	0.019	0.15
LandPC (<i>mu</i>)	0.033**	2.58
VolCAP (Y '000s)	-0.08 [^]	1.74
Volcred	0.411	1.07
Education	-0.056	0.41
Voled	0.595 [^]	1.93
Agehse (<i>hrs</i>)	-0.006	0.55
Volkids	-0.562 *	2.20
Ethnicity	0.234	1.10
Non Han	Reference value	
Constant	0.896	1.12
Observations	286	
Pseudo R^2	0.187	
Likelihood ratio ($\chi^2(19)$)	58.79	
Hits ($y = 1$ if $\hat{p} > 0.5$)	81%	

Table 5.3: The model for propensity score: determinants of participation in the SLCP

The propensity score was estimated using the model described in Table 5.3 above. However, a fully interacted model was estimated in which each explanatory variable was interacted with a dummy representing the presence of voluntary selection into the programme (*Voldum*). However, in order to maintain the ‘balancing’ property required for the matching procedure undertaken in the following Section, the more parsimonious model was used excluding certain interaction terms ³². Using this model the balancing property was satisfied at the 1% significance level meaning that the distribution of the covariates between participants and non-participants was sufficiently similar to satisfy the conditional independence condition. Figure 5.5 in Appendix 3 shows the density of the estimated propensity score for participants and non-participants. This shows that participants and non-participants share considerable support of the propensity score estimated as above, a valuable property for the matching procedure.

5.7 SLCP Programme Evaluation: Matching Estimates of Impacts on Household Income

5.7.1 Income descriptives

The ultimate objective of this Chapter is to establish the impact of the SLCP upon the incomes of participant households. The estimation of the propensity score was a necessary step towards this. The outcome variables for which we estimate the *ATT* are described in Tables 5.4, 5.5 and 5.6. These tables show the different components of real income and their means in Guizhou Ningxia and for the pooled sample respectively, both pre and post SLCP and for participants and non-participants.

Table 5.6 shows that on average there is similarity between participants and non-participants suggesting that these groups are reasonably comparable. Indeed, the similarity between participants and non-participants has already been borne out in the analysis of the propensity score described above and detailed in Appendix 3, in which it was shown that participants and non-participants share much of the support of the propensity score. The comparison at the regional level, however, is not so clear and there are statistically significant differences between the participants and non-participants in terms of the level of incomes within regions, while the composition of incomes differs across regions. Furthermore, the comparison with previous

³²The balancing score is defined by Rosenbaum and Rubin (1983) as a function $b(X)$ such that the distribution of X conditional on this function is the same for the treatment and the comparison groups: $X \perp D | b(X)$.

Pre SLCP				
Income	Participants		Non-participants	
	Mean	Sd	Mean	Sd
Gross	2186.46	2822.15	1212.83	1253.86
Net	1757.67	2407.62	947.62	1247.61
Off-farm	947.87	1805.87	677.41	1134.98
Crop	747.65	1031.55	415.33	353.58
Livestock	289.31	533.84	118.12	209.30
Forest	86.04	811.71	2.22	12.38
Other	131.46	422.09	0.00	0.00
Post SLCP				
Income	Participants		Non-Participants	
	Mean	Sd	Mean	Sd
Gross	2319.2	2703.96	1669.79	1604.22
Net	1908.03	2249.41	1370.95	1645.69
Off-farm	1126.09	1727.88	1088.59	1640.52
Crop	401.77	521.03	473.89	324.16
Livestock	320.31	663.31	94.10	153.77
Forest	3.19	18.05	0	0
Other	136.92	435.56	11.25	63.64
SLCP	298.69	270.32	-	-

Table 5.4: Per capita incomes in Guizhou province (Yuan 2002 prices)

Pre SLCP				
Income	Participants		Non-participants	
	Mean	Sd	Mean	Sd
Gross	1553.44	1276.08	1883.64	2381.73
Net	1120.52	1269.20	1476.69	2223.08
Off-farm	666.84	1041.70	850.27	1378.61
Crop	614.27	376.86	564.02	407.24
Livestock	245.52	502.74	120.99	287.94
Forest	3.95	35.54	23.91	139.73
Other	25.16	179.61	354.87	1888.88
Post SLCP				
Income	Participants		Non-participants	
	Mean	Sd	Mean	Sd
Gross	1940.29	1470.95	2282.91	2480.85
Net	1972.88	2517.39	1739.22	1367.72
Off-farm	966.86	1264.53	1107.01	1558.97
Crop	350.31	308.15	623.19	479.70
Livestock	121.92	374.90	84.14	178.59
Forest	11.69	68.59	33.10	189.82
Other	74.83	493.93	490.55	2159.53
SLCP	376.87	392.31	-	-

Table 5.5: Per capita incomes in Ningxia province (Yuan 2002 prices)

Pre SLCP				
Income	Participants		Non-participants	
	Mean	Sd	Mean	Sd
Gross	1834.79	2126.01	1548.23	1919.38
Net	1403.69	1885.18	1212.16	1809.20
Off-farm	791.74	1435.69	763.84	1256.52
Crop	673.55	743.78	489.67	385.92
Livestock	264.98	516.04	119.55	249.88
Forest	37.65	521.56	12.94	99.04
Other	66.79	303.51	9.59	61.84
Post SLCP				
Income	Participants		Non-participants	
	Mean	Sd	Mean	Sd
Gross	2108.70	2112.77	1976.35	2096.70
Net	1728.24	1834.50	1605.13	1834.50
Off-farm	1037.62	1486.79	1097.80	1588.65
Crop	376.31	415.13	535.94	409.58
Livestock	210.10	530.84	89.12	165.51
Forest	20.00	209.28	17.16	130.73
Other	100.05	458.43	62.51	328.53

Table 5.6: Per capita incomes for the whole sample

estimates of income levels is also revealing.

For example, Table 5.4 shows that our sample is relatively poor compared to samples used for the analysis of the SLCP before. Uchida et al (2004) report that in their participant sample the average per capita income in Guizhou in 2000 is between Y3000 and Y4000, compared to our per capita value of Y2000. Our Ningxia sample is more in line with their findings however with per capita income of around Y2000 compared to their estimation of around Y2500 for the year 2000. These differentials are potentially worrying, particularly when one notices that participants in Guizhou appear to have significantly higher incomes than non-participants in the pre-programme period. The cause of these income differentials is not attributable to one source however and arises from higher average income contributions in livestock, crops, forestry and from off-farm labour. In Ningxia the disparity goes the other way with non-participants having fractionally higher incomes than participants and yet the composition of income is quite similar among productive activities. The disparity narrows in Ningxia in the post programme period suggesting a positive effect on incomes.

That the treatment and control groups differ in observable characteristics is important for the programme evaluation techniques that we use since the identification assumptions for the *DID* estimator imply that outcomes would have evolved in the same way for participants had they not participated as it is observed to evolve for the non-participants. The estimators that we have described above provide a number of techniques, and employ a number identification assumptions which endeavour to control such differences in estimating the programme impacts. In what follows we describe the estimates of our parameter of interest (*ATT*) using parametric, non-parametric and semi-parametric techniques. We also compare unconditional and regression adjusted estimators for completeness. The latter represents an attempt to control for biases that emerge from any mismatching of participants with non-participants and to control any differences in income dynamics that result from observable characteristics. As described above, this has been undertaken with some success in the literature (e.g. Heckman et al 1997, Abadie and Imbens 2002, Navarro-Lozano 2004).

5.7.2 Matching estimates of Average Treatment on the Treated (*ATT*)

Table 5.7 shows the unconditional matching estimates of the impact of the SLCP upon the various components of income using the three programme evaluation methods applied to the levels of the outcome variables. Table 5.8 shows the estimated programme impact using the conditional,

regression adjusted versions of these estimators. There exist a number of non-parametric matching techniques nested in the general formulation shown in Section 5.5.2.1 and 5.5.2.2. For this reason we employed two separate techniques for the propensity score matching: local linear and stratified matching. These techniques reflect different choices of the weights $\sum_{j \in I_0} W_{N_0, N_1}(k, j)$ and $\sum_{k \in I_1} w_{N_0, N_1}(k)$ in (5.12). Local linear matching generates the counterfactual comparison for each programme participant by calculating an a non-parametric local linear regression weighted by the kernel function in which non-participants whose propensity score is closer to those of participants is given more weight than those further away³³. Stratified matching, on the other hand, involves estimating ATT by placing participants and non-participants into intervals of the common support of the propensity score such that the covariates that estimated the propensity score satisfy the balancing property. This ensures that the assignment of households into the participation or non-participation group is considered to be random. ATT is then estimated by taking weighted averages, weighted by the number of observations in each block, of block specific treatment effects. For comparative purposes the results of the stratified matching procedure are presented in Appendix 3 alongside the local linear matching estimates. In each case we assume a common support for the propensity score since it is a requirement for consistency given the identification assumption. This does not reduce the sample sizes considerably due to a large shared support of the propensity score (see Appendix 3).

For regression adjustment we use district level indicator variables to control for locally specific determinants of outcomes. Also, given that selection in to the programme has been shown to be in the basis of agricultural productivity we control for this household variable in the regression adjustment. The same regressors are used in each of the three regression adjusted estimators shown here. In this way we conditioned on observed differences between participants and non-participants over time and control for differences in the dynamics that depend upon these regressors (Abadie 2005). The Abadie estimator that we For brevity we present and discuss the results for each approach only for the case of net incomes in Appendix 5.

In column two of Table 5.7 we have the parametric estimates of ATT_{DID} for each outcome variable, that is, the regression of the difference in the outcome variable upon the dummy variable for participation in the SLCP and a constant. Column three shows the estimates for

³³The nature of the weights depends upon the kernel function chosen and the bandwidth. We chose the Epanechnikov Kernel and some inspection we chose a bandwidth of 0.03. These choices are largely arbitrary however the results were relatively robust to bandwidths ranging from 0.01 to 0.1.

the kernel propensity score matching procedure. In column four the estimates of treatment in the treated are obtained using the semi-parametric approach of Abadie (2005), the method of which is described in Appendix 1.

For all of the results presented below bootstrapped standard errors are calculated and shown in parenthesis. Table 5.7 and 5.8 below show the estimated parameters. Furthermore, Tables 5.7 and 5.8 present results in terms of per capita values. Appendix 4 shows the results at the household level^{34,35}.

5.7.2.1 Discussion of income impacts

The estimates in Tables 5.7 and 5.8 tell largely the same story, although the magnitudes and statistical significance of the estimates differ. Considering Table 5.7 first, we see that the unconditional estimate of the impact of the SLCP on total gross income are negative for participants suggesting that incomes reduced through programme participation. This impact is not statistically significant at the 10% level however. Indeed, the only statistically significant impacts emerging from the unconditional estimates are the expected reductions in crop incomes. The different estimators are broadly similar and suggest that annual household crop income is reduced by between Y200 and Y350 per capita on average for participants. This represents approximately 10% of average per-capita incomes in these regions (Uchida et al 2004). The row labelled 'Crop+SLCP' measures the *ATT* for post programme cropping incomes once the SLCP compensation has been added on. For gross incomes and for all estimators in Table 5.7 this figure is close to zero and statistically insignificant. The implication of this result is that participants are, on average, being fully compensated for their lost crop production. This assumes that the quality of the grain is commensurate with that which is lost. Off-farm incomes are impacted positively while forest and livestock incomes are marginally reduced for participants, although none of these impacts are statistically significant. It should be noted that the Abadie estimator diverges from the parametric and kernel matching estimators in one important case showing larger positive impacts for off-farm labour income: Y179 per capita rather than more modest estimates of approximately Y80. In addition to forest incomes, off-farm labour is considered to be an important alternative source of income to which participant households can

³⁴In order to control for household scale effects the analysis is undertaken at the per capita level (see e.g. Deaton 2000).

³⁵For all tables standard errors are in parenthesis while the symbols ^, * and ** mean significance at 10, 5 and 1% respectively.

Income Sources	ATT on Per capita Income		
Gross Incomes	Parametric	Local Linear	Abadie
Total	-154.20 (158.78)	-14.94 (177.99)	-90.00 (205.67)
Total-SLCP	-496.33** (160.62)	-356.44** (201.23)	-415.42* (195.32)
Crop	-343.50** (75.00)	-280.68** (88.99)	-280.79** (90.43)
Crop +SLCP	-1.37 (68.11)	60.82 (96.19)	42.27 (85.85)
Off-farm	88.08 (122.30)	79.70 (160.50)	179.92 (265.20)
Livestock	-24.46 (65.23)	-23.24 (37.66)	-30.42 (49.26)
Forest	-21.76 (38.22)	-19.27 (17.96)	-26.62 (26.88)
Net incomes			
Total	-68.43 (154.67)	53.24 (180.79)	-40.78 (208.77)
Total-SLCP	-410.56** (154.60)	-288.26** (147.69)	-364.18^ (197.61)
Crop	-248.11** (72.36)	-189.85* (89.96)	-206.40** (83.66)
Crop +SLCP	94.02 (69.79)	151.65* (74.01)	117.66^ (70.03)
Livestock	-25.00 (61.00)	-25.59 (54.76)	-30.43 (53.01)
Forest	-27.52 (35.02)	-21.68 (17.25)	-32.82 (24.81)

Table 5.7: The per capita ATT of the SLCP for the components of household income using matched DID

Income Sources	ATT on Per capita incomes		
Gross Incomes	Parametric	Local Linear	Abadie
Total	354.17 [^] (72.82)	212.06* (95.75)	117.21* (55.00)
Total-SLCP	49.46 (153.62)	-129.44 (93.14)	-114.77 [^] (59.40)
Crop	-265.86** (49.68)	-186.33** (40.92)	-169.49** (34.58)
Crop +SLCP	41.66 (34.70)	155.17** (39.63)	91.39** (24.09)
Off-farm	253.56* (114.85)	336.48** (70.67)	159.09** (65.21)
Livestock	-46.59 [^] (24.98)	-20.00 (35.26)	-56.97** (18.08)
Forest	-17.04 (18.97)	-10.36 (23.16)	-19.38** (6.54)
Net incomes			
Total	340.30* (151.67)	214.78** (84.07)	140.66* (62.59)
Total -SLCP	11.25 (66.55)	-137.89 (94.46)	-114.65* (60.02)
Crop	-216.79** (35.93)	-186.71** (40.82)	-135.79** (25.75)
Crop+SLCP	78.69* (35.04)	154.79** (39.55)	145.14** (24.62)
Livestock	-12.11 (31.75)	-10.65 (37.42)	-85.35** (17.57)
Forest	-18.23 (33.93)	-16.84 (21.26)	-17.20** (6.24)

Table 5.8: Regression adjusted estimators for ATT

turn once their labour is released from cultivation (Uchida et al 2004). As such, the ability to access to the off-farm labour market will be an important determinant of the extent to which the SLCP can induce sustained poverty alleviation and will be an important determinant of the sustainability of the programme itself once compensation ceases. The statistical insignificance of these results do not bode particularly well in this regard.

Of course it is more interesting to look at net incomes. Table 5.7 shows a similar picture. The impact upon total net incomes is again close to zero and statistically insignificant for all the estimators. However, the *ATT* for net crop income is smaller and negative, suggesting input costs have fallen considerably and consequently the net income measure ‘crop+SLCP’ is now positive and significant at the 5% and 10% level for the local linear and Abadie estimators respectively. This shows that once input costs for crop production are taken into account on average the SLCP more than compensates the participants for their change in production. There are nominal decreases in forest and livestock incomes but these are statistically insignificant. That there is no impact upon forest incomes shows the extent to which the participants in the SLCP convert their land to ecological forests rather than productive forests. In our sample, over 85% of participants convert land solely to ecological forest under the SLCP. It also tells of long lead times on income generation in forestry.

However, we should be concerned to test to see whether the estimators of the impact of the SLCP can be further refined. As described above there are a number of reasons why regression adjustment may reduce biases shown to exist for unconditional matching estimators such as those in Table 5.7 (e.g. Heckman et al 1997, Abadie and Imbens 2002). Table 5.8 shows the results once these regression adjusted estimators are employed.

Table 5.8 has some similarities with Table 5.7 in that crop incomes are significantly reduced for participants as expected, and that the *ATT* for livestock and forest incomes are nominally negative and statistically insignificant for the parametric and local linear estimators. However, once the regression adjustment has taken place a number of important distinctions appear in Table 5.8. Firstly, the *ATT* for gross and net total incomes becomes positive and statistically significant for most estimators. In particular, annual total net incomes increase for participants by between Y100 and Y350 per capita. This increase is driven by statistically significant increases in off-farm labour incomes and, of course the SLCP compensation. The latter is evidenced by the increases in net crop+SLCP income component which is statistically significant at least at the 5% level for each estimator

5.7.2.2 Income impacts and sustainability of SLCP

One of the key questions regarding the SLCP is its sustainability once the temporary subsidies cease. It seems clear that for households to maintain forested lands after the cessation of subsidies a minimum requirement is that the welfare of participant households will be at least as high in the absence of compensation as it would be if households were to revert back to their pre-SLCP practices. It is the essence of the programme evaluation problem that we cannot observe the income of households in the counter-factual world, that is, in a situation in which participant households have reverted to former practices, and so the best we can do is generate a counterfactual estimate from our matched comparison groups and simulate this procedure. Tables 5.7 and 5.8 provided one estimate of this comparison in the quantity ‘Total-SLCP’ which effectively measures the impact of the removal of the subsidy from participants. Total-SLCP represents the comparison of participants’ total gross or net income once the monetised value of the SLCP compensation is removed with that of their matched counterfactual. If our estimator is a good one, then this quantity represents the best measure of the income that the participant could obtain if they were to revert back to their former production patterns and income sources. This income measure provides some indication of the impact on participants of the planned cessation of compensation at the end of the programme, given the changes in the composition of incomes that have occurred in the intervening period.

For the unconditional matching in Table 5.7 for both net and gross Total-SLCP the *ATT* is negative and significant for all estimators and is in the region of Y400 per capita per annum. This loss in income comprises of reduced crop, livestock and forest income which remains uncompensated by any increases in off-farm incomes. In short, these results do not bode well for the sustainability of the SLCP since it suggests that once the compensation ceases households will revert back to their original production and labour allocation patterns.

However, net Total-SLCP changes from being large, significant and negative for the unconditional estimators in Table 5.7 to being small, positive and insignificant for the regression adjusted estimators. The exception to this is the Abadie estimator for which a significant negative impact is recorded for Total-SLCP, and for which the positive income changes in off-farm labour income are more conservative. In terms of the sustainability of the SLCP the picture painted in Table 5.8 remains inconclusive. On the one hand the parametric and local linear estimates show that, on average, farmers need not revert back to their former practices upon

the cessation of subsidies since on average income would not be increased by doing so. On the other hand, the Abadie estimator shows that the possibility remains that incomes will fall upon cessation of subsidies since incomes in their absence are lower for participants than they would have been had they not participated. This suggests that there will be winners and losers in the post programme period and hence no general story can be told. Ultimately the decision to reconvert land after the compensation has ceased will be taken at the household level and requires a closer analysis of these decisions. Although in this Chapter we do not analyse individual decisions or post programme intentions this general view is in line with parallel work on these data³⁶. In later Sections the analysis is refined to allow a slightly more detailed look at the issues of poverty alleviation and sustainability.

The regression adjusted estimators differ from the unconditional estimators in their evaluation of the impacts of the programme and yet tell broadly the same story. In sum, the relative *ATT* estimates show that the average impact of the SLCP upon the treated is to shift the composition of income away from crops, livestock and forests towards off-farm sources. The estimators show that, despite these structural changes, the incomes of participants are, on average, only maintained above those of non-participants due to the presence of the SLCP subsidies. The estimators shown tell largely the same story and yet there appear to be some important differences. The next Section discusses these differences further.

5.7.2.3 Unconditional vs regression adjusted results

Heckman et al (1997) undertook a comparative study of the biases associated with a number of different matching estimators, including the regression adjusted and unconditional matching estimators used in this study. Bias was measured against the estimates from a randomised control group. They found that the regression adjusted estimator had a number of desirable qualities. In general this estimator performed better than others especially when omitted time invariant characteristics are an important source of bias. We have motivated these estimators on the basis of their ability to accommodate this type of heterogeneity. Secondly, they found that, although in their study the simple *DID* or matching methods often had a lower overall bias, the regression adjusted *DID* estimator had a much lower pointwise bias. That is, the low overall bias resulted from large equal yet opposite pointwise biases which coincidentally cancelled out. The regression adjusted estimator is less likely to be biased in any given situation

³⁶Grosjean (2005) provides an analysis of stated post programme intentions of the households in our sample.

it is argued. In addition, the regression adjusted estimator was shown to be more robust to alternative specifications of the propensity score. Other applications have found that regression adjustment provides more refined estimates of treatment effects. Glick et al (2004) find that controlling for a number of country level characteristics not included in the estimate of the propensity score improves the significance of treatment effects of capital market liberalisation for example. Abadie et al (2001) also provide evidence for the reductions in bias resulting from mismatching that regression adjustment allows for.

In our case one positive feature of the regression adjusted estimates of Table 5.8 is that the standard errors are generally smaller than those of Table 5.7, with the Abadie estimator dominating the others in this respect. The regression adjusted estimates are more accurate³⁷ either as a result of the refined matches for the treatment group or due to the ability to control for the variables upon which the selection rule depends and other geographical differences between participants and non-participants that may affect the level and dynamics of the outcome variables over time. The use of geographical variables and the pre-programme agricultural productivity endeavour to do this. In sum, although we cannot test the extent of biases associated with our estimators against a randomised control experiment. It is solely on the basis of these arguments and the features of the estimates that we are inclined to prefer the regression adjusted estimates in Table 5.8.

5.7.3 Summary of average impacts (*ATT*)

The programme evaluation results are again partly in line with expectations given the nature of the programme. On average SLCP participants have lower cropping and livestock incomes. The released labour shifts on average towards off-farm activities as an alternative income source. That there is no significant increase in forest incomes however reflects the fact that there are long lead times for forest products and also that ecological forests are the rule rather than the exception. Some differences emerge between the estimators in this analysis, with the regression adjusted estimators being preferred for the reasons described above.

Using the average treatment effect for ‘Total-SLCP’ as a crude measure of the sustainability

³⁷However, some authors have noted that the *DID* estimator can occasionally generate estimates of the standard error that are biased downwards (Bertrand et al 2003). Bootstrapping procedures that we undertake here offer a potential solution to this problem. Ultimately the comparison between unconditional and regression adjusted *DID* estimators on the basis of standard errors remains valid though.

of the SLCP we find no strong evidence either way with regard to likely post programme behaviour. None of the impact estimates for this quantity are strongly statistically significant suggesting that on average households are indifferent between maintaining SLCP land and reconverting. Clearly, however, post programme behaviour is a household level decision and differences will and do exist between households in this regard.

In the following Section we undertake programme evaluation of a difference sort focussing more closely upon the impact of the SLCP on features of the distribution of income. In this way we are able to make clearer statements about the extent to which the SLCP has contributed to poverty alleviation and say something more specific about the types of households for whom we can expect sustained participation in the SLCP even after the compensation stops.

5.8 Poverty Alleviation the Distribution of SLCP Impacts

5.8.1 Quantile Treatment Effects ($QTE(\tau)$)

The average treatment effect is a useful measure for the impact of a policy or intervention. The previous Sections have provided us with estimations of the average treatment on the treated (ATT) for a variety of important outcome variables. However, although this parameter is of interest when we want to investigate the average impact of the programme for participants, and hence it can tell us something about the relative costs and benefits of the policy, the average is a rather crude measure of the impact. It is a summary statistic of the entire distribution of matched impacts and therefore, although we have been careful to allow for heterogeneity of impacts across households, this statistic does not reflect changes in the distribution of the outcome variable³⁸. However, for a variety of reasons we are interested in understanding the impact of the programme on other features of the distribution of the outcome variable. Not only does the theory of household behaviour outlined above suggest that responses to interventions will be heterogeneous, the SLCP's poverty alleviation objective mean that it is of interest to discover the extent to which participation in the programme has affected low income households.

Quantile regression provides another mode of analysis which allows us to model the impact

³⁸So far the assumption in the parametric *DID* model has been that the *ATT* has been the same for all participants. We could have made the impact conditional on certain characteristics of X by generating interaction effects (Abadie 2005). Both cases fall under the 'constant treatment effect' umbrella. As described above, the non- and semi-parametric matching estimators relax this assumption for the calculation of *ATT*. Heckman (1998), for example, discusses relaxing this assumption further.

of the programme at different quantiles, τ , of the income distribution. The parameter of interest here is generally known as the quantile treatment effect or $QTE(\tau)$ and as above we estimate the impact on the treated. Quantile regressions have a number of advantages over mean regressions including providing more detailed descriptive analysis across the distribution of the outcome variable than simple mean analysis, robustness to distributional assumptions and the ability to deal with censored data³⁹. Not only that, but inter-quantile regression allows us to understand the impact of the programme on the distribution of incomes, that is, one can estimate the impact of the programme on inter-quantile ranges. In the case in hand the robustness quality is of particular importance given the skewed nature of income distributions.

In this Section we present two approaches to quantile regression as explained concisely in Athey and Imbens (2005), and Ho et al (2004). Each of these methods exploit our panel data and estimate the quantile treatment effect via difference in differences methods. In particular, the difference in differences $QTE(\tau)$ is defined by:

$$QTE(\tau) = (F_{11}^{-1}(\tau) - F_{10}^{-1}(\tau)) - (F_{01}^{-1}(\tau) - F_{00}^{-1}(\tau)) \quad (5.29)$$

where $F_{it}(y)$ is the distribution function for the outcome variable, y , for a person of participant status $i = 0, 1$ for non-participants and participants respectively, at time $t = 0, 1$ for pre and post-participation⁴⁰. In this way individual specific heterogeneity is swept out in a manner similar to the analysis of *ATT* above allowing for our behavioural model to remain valid⁴¹. The difference between the two quantile regression estimates shown here is the data used to obtain the sample analogue of (5.29)⁴².

Firstly, following Athey and Imbens (2005), we undertake a simple parametric quantile treatment effect model using the quantile regression version of the unconditional model in (5.17). Secondly, we follow Ho et al (2004) and undertake a matched quantile regression using the counterfactual data generated by our local linear regression adjusted matching procedure

³⁹Koenker and Basset (1978) provide a summary of the relative advantages and disadvantages of quantile versus mean regression.

⁴⁰Inference for these estimates is well established. See for example Koenker and Basset (1978). Standard errors are bootstrapped once more with 100 repetitions.

⁴¹Meyer et al (1995) and Poterba et al (1995) provide applications of quantile regression to panel data along these lines.

⁴²Athey and Imbens provide a highly intuitive account of these estimators in addition to an alternative *DID* estimator for $QTE(\tau)$.

Net income		Unmatched (<i>obs</i> : 572)		Kernel Matched (<i>obs</i> : 864)	
Quantiles(τ)		$QTE(\tau)$	Std. Err.	$QTE(\tau)$	Std. Err.
25%	607.75	366.48**	76.39	330.96**	131.19
50%	1115.69	451.21**	98.98	472.85**	145.19
75%	2133.89	140.82	236.04	286.26	334.61
Net income post programme					
25%	591.41	-31.56	104.49	18.362	94.29
50%	1122.50	-64.00	135.33	84.656	114.31
75%	2188.75	-145.74	310.27	-15.459	246.67

Table 5.9: Quantile treatment on the treated for net incomes

described above. This is our matched $QTE(\tau)$. In each case we analyse the treatment effect of the SLCP on the 25%, 50% and 75% quantiles of the income distribution.

Table 5.9 shows simultaneous quantile regressions for the 25%, 50% (median), 75% quantiles of two outcome variables: net income with compensation and net income without compensation. As before the latter measure of income provides us with some idea of the post programme income levels at the selected quantiles of the distribution.

A number of things are worth noting here. Firstly, the unmatched and matched quantile treatment effects tell the same story by and large. The 25% quantile treatment effect is positive and significant at the 1% level, as is the slightly larger statistically significant impact upon median (50%) incomes for both methods. The impact upon those at the highest quartile of the distribution is low and insignificant both statistically and economically. The impact of Y366 and Y330 upon the lowest quartile represents an increase of approximately 50% of per capita income, which is considerable. The impact of Y451 and Y472 represents approximately 40% of pre-programme median per capita income. This suggests that the positive estimates for the *ATT* for net income noted in Tables 5.8 and 5.7 in Section 5.7.2 are observed as a result of increases in the lower quantiles of the income distribution.

These results show that the SLCP is making positive and progressive changes to the incomes of poor farmers despite the loss of land use. In some ways this is to be expected since a policy which offers a fixed amount of compensation for setting aside land will benefit more those whose productivity on land is lowest and this is a feature frequently associated with poor households.

The compulsory nature of the programme means, however, that some high productivity households are chosen to be participants and as such compensation may not sufficiently account for lost production. It appears that these households are in the higher income quantiles judging by the insignificant impact upon the income of the 75% quantile.

The impact upon poverty arising purely from compensation is temporary like the compensation itself. Permanent increases in income for low income households will only arise if households have no incentive to revert back to former production patterns when the compensation ceases. Given this we ought to be concerned with changes in income sources brought about by participation in the programme. Section 5.7.2 showed that off-farm income was the most important substitution taking place for participants and as such the potential for the programme to induce participation in this market will be an important determinant of the sustainability of the programme. Work undertaken elsewhere on these data shows that on average there is a positive impact on the propensity to participate in off-farm activities for participants in the SLCP (Grosjean 2005). Although this says nothing about the impact at different quantiles of the income distribution, together with analysis of average impacts, and the average impacts for participants and non-participants in the off-farm labour market shown in Table 5.13 in Appendix 4, it suggests that the positive effect in Table 5.9 for lower quantiles arises is partly due to this shift in labour allocation⁴³.

In summary, the compensation policy is sufficiently well targeted towards the poorest to ensure significant increases in incomes for the poor. There are two reasons why this may be occurring. Firstly, the compensation for loss of crop incomes outweighs the value of the crops for household on the lower quantiles of the income distribution. Secondly, low income households may have been more successful in finding alternative incomes. The sustainability of the programme is dependent upon the extent to which the latter adjustments represent permanent increases in welfare.

In order to provide some indication of the latter we analysed the quantiles of net income with the compensation removed. The lower panels of Table 5.9 shows that, although all the estimates are negative, there is no statistically significant difference between participants and

⁴³Grosjean (2005) provides some analysis of this response. In addition, if the quantile regression described above is undertaken with an interaction term for participation in the SLCP and participation in the off-farm labour market dummy the associated coefficients are positive and significant for the 25% and 50% quantiles. These results are preliminary however and are not shown due to their inherent endogeneity problems and represent the focus of future work.

non-participants at any quartile once compensation is removed. Given the significant decrease in cropping incomes shown in Section 5.7.2 this suggests that participants at each quartile have found alternative sources of income in a manner described in Table 5.8 above. Given that the counterfactual comparison group represents the best estimate of the potential income of the participants had they not been participants, this suggests that incomes would not be significantly raised by reverting back to former land-uses.

The use of quantiles of the distribution of the outcome variables provides another layer of descriptive analysis of the impact of the SLCP upon households. What we have shown here provides the beginning of a more detailed analysis of the extent to which the impact of the programme is heterogeneous among income groups. Hence it provides a measure of the extent to which one of the fundamental objectives of the programme: improving the incomes of the poor, is being achieved both during the programme and, to some extent, in the post programme period. However, the question remains, although we have shown positive impacts on income for participants of the SLCP, to what extent have households been lifted out of poverty by any useful measure? We turn to this in the following Section.

5.8.2 Poverty alleviation

5.8.2.1 Poverty lines

The previous Section has shown that the programme has different heterogeneous effects upon households at different points of the income distribution. In particular the positive average treatment on the treated noted in Section 5.7.2 appears to be arising from increases in the incomes in lower quantiles of the distribution of incomes. This implies that the programme is targeting the poor as intended and potentially lifting these households out of poverty. In this Section we analyse the implications of these findings for the alleviation of poverty and assess the extent to which participant households are indeed being lifted out of poverty. Using the data generated from the programme evaluation techniques used above we analyse the impact of participation in the SLCP upon further features of the distribution of incomes in order to test the poverty alleviation qualities of the programme.

Of course, the extent to which poverty alleviation takes place is dependent upon the definition of the poverty lines. Many definitions exist and are used in practice. Frequently, in rural semi-subsistence and autarkic households the poverty line is determined by reference to

the amount of grain produced per capita in a given household (Park and Wang 2001). There are many multi-dimensional measures of poverty: the Human Development Index and Human Poverty Index (UNDP 2004) provides an oft cited example. One of the most universally applied poverty lines is \$1 per capita per day, that is, households that spend less than an average of \$1 on consumption each day are considered to be poor. With regard to income the measure is frequently set at \$2, but in each case a conversion to local currency using purchasing power parity (PPP) is required.

The choice of poverty line has received much attention in China and recent studies plotting China's progress in alleviating poverty have employed a wide variety of poverty lines each differing in their rationale and monetary value. Furthermore, the official poverty line in China also differs from those widely used for international comparisons. In short, poverty and poverty alleviation are measured by a variety of yardsticks. For example, the official poverty line for 2002 in China is Y637 per capita per year. This figure is based upon the cost of minimal calorific intake (2100Kcal/day) and some non-food consumption for basic necessities (Park and Wang 2001). This translates into approximately \$0.75 per day in Purchasing Power Parity terms (PPP)⁴⁴. More recently, the official poverty line has been increased to Y882. Coincidentally, this poverty line translates into the \$1 per capita per day (PPP) yardstick commonly used as an international poverty line for consumption. There has been much debate concerning the appropriate level at which to measure the incidence of poverty in China, with one common feature of this discussion being that the official poverty line is too low and hence underestimates poverty (Reddy and Minoiu 2005). This has lead other researchers to use higher poverty lines such as \$1, \$1.5 and \$2 per day in PPP terms used by Fang and Fan (2002), Chen and Wang (2001) and Sala-i-Martin (2002) respectively. The highest poverty line that this author has found applied in China was Y2152 per capita per day, but the precise rationale for this measure remains unclear (Xue and Zhong 2003, quoted in Reddy and Minoiu 2005).

Naturally, differences in the measure of poverty lead to differences in the measurement of the extent of poverty alleviation. Indeed, along with the discussion of the baseline level of poverty, biases in the rate of change in the statistics over time and disagreement on how to calculate the cost of living in particular regions, the choice of poverty line has given rise to large literature discussing the measurement of the Chinese government's progress in this regard (e.g. Yao 2000, Park and Wang 2001). There is general agreement that significant progress has been

⁴⁴The PPP conversion factor applied by the World Bank is Y1.78:\$1

made to lift rural households out of poverty during the last 20 or so years. The disagreement centres on the extent of this lift. The official estimate from the Chinese National Bureau of Statistics suggests that the 90's was the most successful decade during which two thirds of the rural poor were lifted out of poverty. Worryingly, however, recent years have seen something of a reversal of this trend, with rural poverty rising by 3% between 2002 and 2003 (Reddy and Minoiu 2005). Reddy and Minoiu provide a detailed analysis of poverty alleviation under different assumptions for the calculation of the \$1 PPP levels in China and find a less optimistic picture, as do Khan and Riskin (2001).

Commonly, the measurement of poverty against a single poverty line is considered a sufficient test for poverty alleviation. However, recent work by Chen and Ravallion (2003) reveals that the choice of poverty line is of considerable moment when undertaking programme evaluation and the reliance upon one poverty line for comparison may hide the real impact of the programme. For example, programme evaluations of the World Bank poverty alleviation interventions such as the South West Poverty Reduction Programme, reveals that the impact of the programme, that is, the numbers of households lifted above the poverty line, was minimal when measured from the perspective of the \$1 per day (Chen and Ravallion 2003). Not only did they discover that the impact was much larger when compared to the lower official poverty line of Y800, they also found that the impact varied widely across poverty lines. In this sense, and in light of the heterogeneous impacts estimated in the previous Section, it makes sense to test the impact of the SLCP against a variety of poverty lines. There are a great many reasons in the case in hand why a similar analysis will be useful with regard to the SLCP. Beyond measuring any success in alleviating poverty, by establishing the winners and losers from a the SLCP we will gain a better understanding of those households who would be most likely to reconvert land once subsidies cease. That is, we can go some way to identifying the likelihood that the programme is sustainable.

Given the disputes concerning appropriate poverty lines, in this Section we follow the approach of Chen and Ravallion (2003) in analysing the impact of the SLCP on the incidence of poverty, recognising the fact that the impact of the programme need not register at any predefined poverty line and hence an analysis across a number of definitions is important.

5.8.2.2 SLCP impact on poverty alleviation

In this Section we measure the impact of the SLCP upon poverty alleviation, that is, the proportion of households considered to be living in poverty. One clear way in which to measure changes in the proportion of people living at or below a given income level is to observe the change in the cumulative distribution function for income (CDF). Figure 5.2 shows that during the period covered by our data (2000-2004) there has been significant reductions in poverty by most measures across all the households in our sample. Figure 5.2 shows the change in the CDF for net income for the entire sample of participants and non-participants since the pre programme period. The difference is negative showing that the proportion of households below any of the income levels shown in Figure 5.2 is higher in the pre-programme period. For example, from the perspective of the official poverty line of Y640, there has been a 15% drop in the number of households falling below this level. Indeed the largest changes in the CDF have occurred at the lowest quantiles of income. Of course, this does not reveal the impact of the programme in this respect, but rather general trends of poverty alleviation. Statistical significance is achieved at approximately -5%⁴⁵.

Figure 5.3 shows the local linear matched differences in differences estimates for the cumulative distribution function (CDF) for per capita net incomes. Here we have calculated the vertical difference between the CDF for participants net incomes (post minus pre) and then subtracted the same measure for non-participants, where the non-participants incomes were assumed to be the counterfactual incomes calculated from the matching procedure undertaken in Section 5.7.2. Appendix 6 shows the same statistic for the stratified matching and the unmatched *DID* techniques. In each case the outcome is largely the same in that the major improvements in net income have arisen in the lowest income quantiles, particularly, those below Y1500, while the programme has had a benign effect upon those in the higher income quantiles compared to non-participants. Indeed, the stratified matching result even suggests that the higher income quantiles may have suffered as a result of participation in the programme. One explanation for this, remembering that in large part the programme is implemented involuntarily in our study area, is that uniform compensation may not have been sufficient to compensate the losses of richer, more productive households, whereas the opposite is true for poorer households. This may reflect the findings of Uchida et al (2004) who suggested that targeting was not always

⁴⁵In this section, significance is determined using probit analysis on the probability of being poor given a particular poverty line. The results are not shown here.

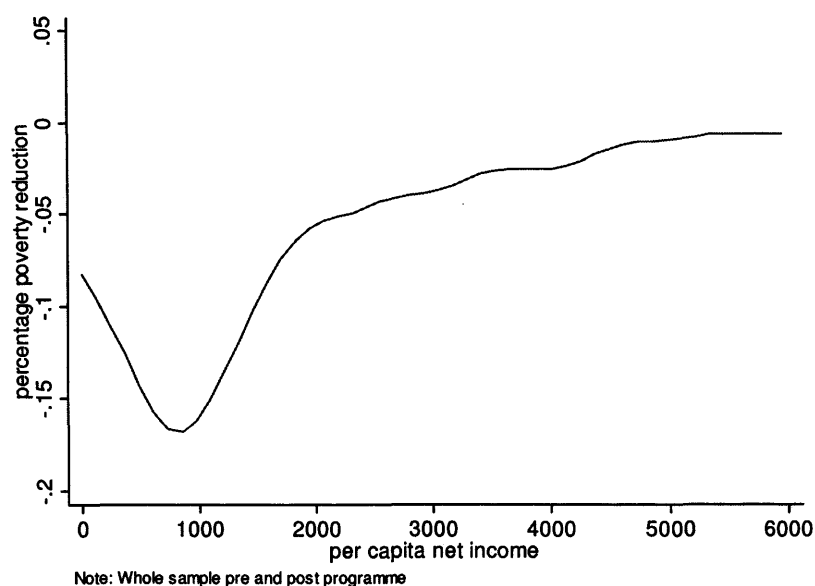


Figure 5.2: Trend in income poverty

cost effective in this regard.

Despite having shown the impact of the programme across a wide variety of poverty lines, in order to fix ideas we discuss the three particular poverty lines commonly used in China and beyond: the official poverty line of Y640, the \$1 a day value of approximately Y900 and the higher value of \$2 per day (Y1800) frequently used as a measure of income poverty (see e.g. Sala-i-Martin 2002). In this way we can assess the impact of the programme in terms of previous work. Figure 5.3 shows that in terms of the income poverty line of Y1800 per capita the programme has had a minimal effect with a reduction in poverty close to 0%. This is true of the alternative techniques shown in Appendix 6. That is, even though Figure 5.2 showed that there have been improvements by this yardstick for the entire sample, the change over time in the number of people that are at or below this level of income does not differ between matched participants and non-participants in the SLCP. At the lower poverty lines however, this is not true and it appears that the SLCP has had a significant poverty alleviation effect when measured from the lower official poverty line or even the \$1 per day measure (Y900). Again, this pattern is repeated across the different techniques used. At the official poverty line, the SLCP compensation has reduced poverty by approximately 10% points. Statistical significance here is at approximately -4%.

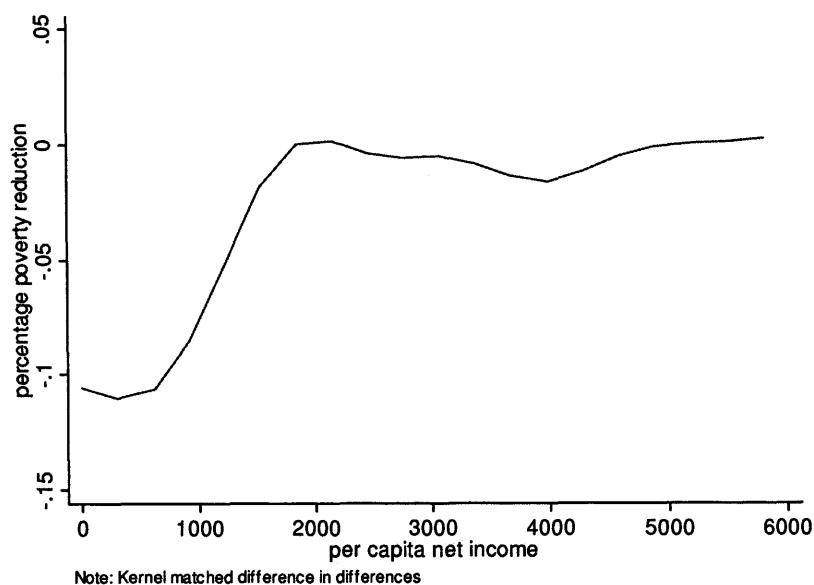


Figure 5.3: SLCP impact on income poverty

Of course, of critical importance for the long-term success of the SLCP is the post programme impact. If the SLCP is to achieve both of its targets of environmental benefits and poverty alleviation in the long-term it is important that outcomes are improved for participants even when the compensation ceases. We have very little to bring to bear on this issue in this Chapter apart from considering whether households have found sufficient alternative sources of income, and effectively increased the opportunity cost of their labour in cultivation, such that even in the absence of SLCP subsidies households are not tempted to return to their previous modes of production. We do this here as we have above by simulating the cessation of subsidies and analysing matched differences in differences of the CDFs for net income with the SLCP subsidies removed from the post programme income. Figure 5.4 shows the outcome.

Figure 5.4 shows that once subsidies are removed, the impact of the programme is to increase the number of participant households in the lower quantiles of the net income distribution compared to counter-factual non-participant households. Statistical significance is attained at approximately +7%, that is approximately between Y1200 and Y1700. What are the implications of this? One implication is that some participant households will be able to improve their lot by reverting back to former land uses once compensation ceases. This would imply that the poverty alleviation afforded by the SLCP shown in the previous figures, and reflected in the

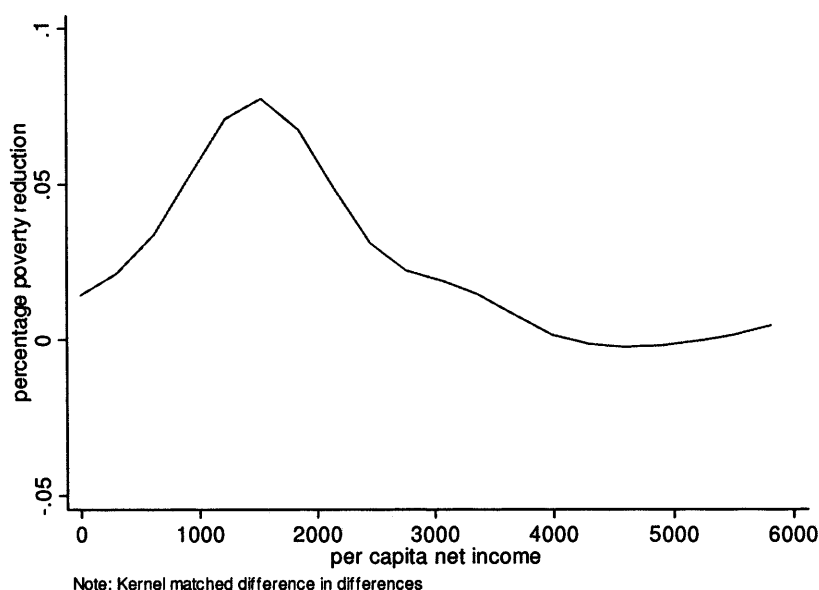


Figure 5.4: SLCP impact on income poverty: Post programme without subsidies

quantile treatment effects, will have been transitory⁴⁶.

Of course, although illustrative of the immediate impact of the cessation of subsidies, this is a slightly naïve analysis of post programme behaviour. Hence, this is a bold prediction since there may be other courses of action available. Despite this, it is not without some corroborating evidence. Work undertaken on these data by Grosjean (2005) has shown that just over 60% of participating households registered an intention to reconvert land in the event that compensation ceases. This intention was shown to be influenced negatively by participants ability to find alternative incomes, particularly off-farm incomes, again fitting in with the findings in this Chapter⁴⁷.

⁴⁶One question arises here. Why is there a significant increase in the probability of falling beneath the poverty lines measured between Y1200-Y1700, when the quantile regression did not pick up any significant difference between participants and non-participants once compensation had been removed. The answer lies in the fact that the latter analysis is based upon a count of households beneath the poverty line regardless of whether the monetary impact was statistically significant.

⁴⁷The probability of reconverting post programme was also heavily influenced by a number of other institutional factors such as security of property rights to SLCP land, the mode of programme implementation: voluntary/involuntary, whether or not farmers participated in the choice of tree varieties, and participation in rental markets (Grosjean 2005).

5.9 Conclusion

The SLCP was hatched in direct response to the loss of topsoil, siltation of streams and severe flood events witnessed in the Yangtze river basin in 1998. The blame for the severity of these floods was placed squarely with deforestation resulting from the cultivation of sloped lands in the upper reaches of these river basins (World Bank 2001). The objectives of the SLCP are therefore twofold. Firstly, the SLCP endeavours reduce these basin wide environmental damages by reforesting cultivated sloped land. The second objective of the SLCP is to reduce poverty among the rural households cultivating these sloped lands. Both of these objectives are achieved by way of relatively generous yet temporary compensation packages consisting of cash, grain and occasionally seedlings and technical assistance. The impact of the programme has been impressive with regard to the first objective, with approximately 1.2 million hectares of mainly sloped land converted to forest. With regard to the second objective the evidence thus far is less clear, with previous estimates suffering from a number of important data shortcomings and econometric problems, particularly sample selection. In short, the extent to which household incomes have been increased by the programme is not at all clear (Uchida et al 2002).

Above all however, there is concern that these environmental gains will only have the longevity of the compensation itself. That is, once the compensation ceases, participants will simply revert back to their former land-use practices. This is almost certain to happen if the temporary compensation fails to induce permanent increases in household incomes and hence in many cases, permanent release from poverty. It is easy to see that the two objectives of the SLCP are very much linked when viewed in this light since, in the long-run, the first objective will not be achieved without the second. Moreover, permanent poverty alleviation will only be achieved if temporary compensation for reforestation induces households to find alternative and more lucrative sources of income to the extent that they are better off even in the absence of the compensation.

In this paper we estimate the impact of the programme on the incomes of participant households using programme evaluation techniques applied to panel data commonly employed in the evaluation of active labour market programmes (Blundell and Costa-Dias 2000), but frequently and increasingly used in the evaluation of public and donor interventions in developing countries (e.g. Chen and Ravallion 2003, Park et al 2001, Bhandyopadhyay 2004). These techniques allow us to accommodate the econometric problems that have plagued previous analyses, namely

non-random participant selection based on observable and unobservable household and local heterogeneity and the potential for heterogeneous programme impacts across households. We estimate average treatment on the treated (*ATT*) for incomes in total (gross and net) and each of the sources of income represented in our data: on-farm income (crop, livestock, forestry) and off-farm income, using a number of estimators based on the propensity score: matched difference in differences (Heckman et al 1998) and a new more efficient approach from Abadie (2005). Each of the non/semi-parametric estimators used has its roots in the parametric approach to programme evaluation of Ashenfelter and Card (1985), which is also estimated here.

We find that, using our preferred estimators, the SLCP has had a positive impact on net incomes for participants compared to non-participants over the time period. This increase in net income has arisen from two sources. Firstly, on average the SLCP compensation outweighs the opportunity cost of cultivated land, and secondly, participant households obtain more of their incomes from off-farm sources. Livestock and forestry incomes have decreased for participants. We then undertake a simulation of the cessation of compensation by comparing incomes net of compensation for participants to the counterfactual control group and find that the differences are negative yet not significant. This provides some, albeit weak indication that were the SLCP compensation to end today, given the choice households could increase their income by reverting back to former practices.

Mindful that the average treatment effect may hide heterogeneous impacts for different income groups, and given our interest in understanding the impact of the programme on the poor, we undertake a matched quantile regression analysis following Athey and Imbens (2004) to estimate the quantile treatment effects (*QTE*). The analysis shows that the impact on net incomes has been significant both statistically and economically for the lower quartiles of the income distribution (25% and 50%) but not for the upper quartile (75%). That is, the impact of the programme has been most pronounced on the incomes of the poorest increasing their incomes by approximately 40% in some cases. Unlike the average estimates, quantile regression estimates are robust to distributional assumptions.

The heterogeneity of the impact across households at different quantiles of income means that the impact of the programme on poverty alleviation is likely to differ depending upon the yardstick against which it is measured. Such is the finding for other poverty alleviation strategies in China (e.g. Chen and Ravallion 2003). We use difference in differences to test the impact of the SLCP on poverty alleviation against a continuum of poverty lines we find that this

is indeed the case. When considered from the \$2 (Y1800 in PPP) per capita per day poverty line used internationally to measure income poverty, we find that the impact of the programme is negligible. However, at the official poverty line in China of Y640, and the \$1 (Y900) per capita per day poverty line, the reduction in poverty as a result of participation is large and significant. However, on performing the same simulation of the cessation of compensation as above, it is shown that the proportion of households living beneath the lower poverty lines is significantly higher for participants. Again, this provides weak evidence for the assertion that households would revert back to their former land-use practices when the compensation ends given the choice.

In summary, the SLCP appears to have targeted poor households well and the combination of temporary compensation and the ability to find or increase off-farm labour income has improved the lot of the poor by increasing their incomes and lifting many households out of poverty by most reasonable measures. However, there is some evidence to suggest that these gains may only have the longevity of compensation itself. Although the simulations used are quite naïve, their conclusions correspond to other work on the post programme intentions of the farmers in these data which suggests that up to 60% of participants intend to revert back to former land-uses once the compensation ends (Grosjean 2005). The evidence presented in this Chapter suggests that the targeting of the programme leads to poverty alleviation, however the beneficial impact of the programme is unlikely to be sustainable.

Some important caveats need to be stated. Firstly, our outcome measure is income which is well known to be a noisier variable than other measures of household welfare such as consumption (Deaton 2000 Besley 1995). Secondly, it is also well known that incomes are likely to be understated when elicited by household survey. Deaton (2000) suggests that in some cases income reported in household surveys may only be 60% of that recorded in national accounts for example. In the other direction, our constructed income variable may have overvalued certain components of income by using elicited market prices for producer consumed produce. Lastly, although we have pre and post programme data, the analysis could always be improved by obtaining data from additional time periods.

What is clear from this work is that the analysis of the impact of the programme could benefit from a more detailed evaluation of the impact of the programme on off-farm labour decisions. In the absence of increases in forest or livestock incomes, the ability to find off-farm labour income appears to be the one adjustment to household production that is critical in

determining the sustainability of the SLCP.

5.10 References

Abadie A (2005). Semi Parametric Difference in Differences. *Review of Economic Studies* 72(1).

Abadie A, Drukker D, Herr Leber J and Imbens G W (2001). Implementing Matching Estimators for Average Treatment Effects in STATA. *The Stata Journal* 1(1) p1-18.

Abadie A, Angrist J and Imbens G (2002). Instrumental Variables estimates of the effect of subsidized training on the quantiles of trainee earnings. *Econometrica* 70(1), pp91-117.

Abadie, A. (2003), "Semiparametric Instrumental Variable Estimation of Treatment Response Models", *Journal of Econometrics*, 113, 231-263.

Bandyopadhyay S, Shyamsundar P, Wang L and Humavindu M N (2004). Do households gain from community-based natural resource management? An evaluation of community conservancies in Namibia. Department of Environmental Affairs, Research Discussion Paper Number 68. Ministry of Environment and Tourism, Government of the Republic of Namibia.

Bell, B., Blundell, R. and Van Reenen, J. (1999), "Getting the Unemployed Back to work: An Evaluation of the New Deal Proposals", *International Tax and Public Finance*, 6, 339-360.

Bertrand M, Duflo E and Mullainathan S (2002). How much should we trust Difference in Differences Estimates?. NBER Working Paper No. 8841.

Blundell, R. and M. Costa Dias (2000), "Evaluation Methods for Non-Experimental Data", *Fiscal Studies*, December 2000, Vol. 21, no. 4, pp. 427-468.

Blundell, R., Costa Dias, M., Meghir, C. and Van Reenen, J. (2002), "Evaluating the Employment Impact of a Mandatory Job Search Assistance Program", IFS working paper W01/20 (www.ifs.org.uk)

Blundell, R., Dearden, L. and Meghir, C. (1996), "The Determinants and Effects of Work-Related Training in Britain", London: Institute for Fiscal Studies.

Bowlus, A. and T. Sicular, (2003), Moving Towards Markets? Labor Allocation in Rural China, *Journal of Development Economics*, 71 (2003), 561-583.

Benjamin D, Brandt L & Giles J (2004). The Evolution of Income Inequality in Rural China. William Davidson Institute Working Papers Series 2004-654, William Davidson Institute at the University of Michigan Business School

Carter, M. and Y. Yao (1999), Specialization without Regret: Transfer Rights, Agricultural Productivity and Investment in an Industrializing Economy, World Bank working paper.

CCICED (2002). Implementing the Natural Forest Protection Programme and the Sloping

Land Conversion Programme. Experiences and Lessons, 72.

Chen S and Ravallion M (2003). Hidden Impact? Ex-Post Evaluation of an Anti-Poverty Programme. Development Research Group, World Bank, Washington DC.

Chernozhukov V and Hansen C (2005). Notes and Comments: an IV model of quantile treatment effects. *Econometrica* 73(1), pp245-261.

Deaton A (2000) The Analysis of Household Surveys. A micro econometric approach to development policy. World Bank, Washington DC.

Deaton, A. (1988), Quality, Quantity, And Spatial Variation of Price, *American Economic Review*, Vol. 78, 418-430.

deBrauw A, Huang J, Rozelle S, Zhang L and Zhang Y (2002). The Evolution of China's Rural Labour Markets during the Reforms. *Journal of Comparative Economics* 30(2), p329-353.

Deininger, K. and S. Jin (2002), Land Rental Markets as an Alternative to Government Reallocation? Equity and Efficiency Considerations in the Chinese Land Tenure System, World Bank Policy Research Paper 2930, Nov. 2002.

Deininger, K. and S. Jin (2002), The Impact of Property Rights on Households' Investment Incentives, Risk Coping and Policy Preferences, World Bank Policy Research Paper 2931, Nov. 2002.

Dong, X. (1996), Two Tier Land Tenure System and Sustained Economic Growth in Post-1978 Rural China, *World Development*, Vol. 24, No. 5. (1996), 915-928. 57

Evenson R E and Mwabu G (1998). The Effects of Agricultural Extension on Farm Yields in Kenya. Center discussion paper # 798. Economic Growth Center, Yale University.

Feder, G., L. Lau, J. Lin and X. Luo (1990), The Relationship between Credit and Productivity in Chinese Agriculture: a Microeconomic Model of Disequilibrium, *American Journal of Agricultural Economics*, Vol.72(4), 1151-1157.

Glick R, Guo X and Hutchison M M (2004). Currency crises, capital account liberalisation and selection bias. Santa Cruz Center for International Economics working paper 04'14. University of California, Santa Cruz.

Gong Y and Xu J (2002). Case Study on the Conversion of Farmland to Forest and Grassland in Dafang County, Guizhou Province. Centre for Chinese Agricultural Policies, Chinese Academy of Sciences, Beijing.

Greene W (1995). *Econometric Analysis*. 4th Edition, Prentice Hall.

Grosjean P (2005). The impact of land set aside programmes in labour allocation choices of peasant households under market failures. mimeo, University College London.

Halaby C (2004). Panel Models in Sociological Research: Theory into Practice. *Annual Review of Sociology* 30, p507-544.

Härdle, W. (1990). *Applied Nonparametric Regression*, Econometric Study Monographs. Cambridge: Cambridge University Press.

Heckman J, Ichimura H and Todd P (1998). Matching as an Econometric Estimator. *Review of Economic Studies*, 65, p261-294.

Heckman, J. and Robb, R. (1985), "Alternative Methods for Evaluating the Impact of Interventions", in *Longitudinal Analysis of Labour Market Data*, New York: Wiley.

Heckman, J. J. (1990), "Varieties of Selection Bias", *American Economic Review*, 80, 313-318.

Heckman, J. J., Ichimura, H. and Todd, P. E. (1997), "Matching as an Econometric Evaluation Estimator: Evidence from Evaluating a Job Training Programme", *Review of Economic Studies*, 64, 605-654.

Heckman, J. J., Ichimura, H., Smith, J. and Todd, P. E. (1998), "Characterizing Selection Bias using Experimental Data", *Econometrica*, 66, 1017-1098.

Heckman, J., Ichimura, H. and Todd, P. (1998a), "Matching as an Econometric Evaluation Estimator", *Review of Economic Studies*, 64, 605-654.

Heckman, J., Ichimura, H., Smith, J. and Todd, P. (1997), "Characterising Selection Bias Using Experimental Data", *Econometrica*, 66(5), 1017-1098.

Heckman, J., LaLonde, R. and Smith, J. (1999), "The Economics and Econometrics of Active Labour Market Programs", in A. Ashenfelter and D. Card, eds., *Handbook of Labour Economics*, vol. 3, Amsterdam: Elsevier Science.

Heckman, J and Smith J. 2004. "The Determinants of Participation in a Social Program: Evidence from a Prototypical Job Training Program." *Journal of Labor Economics*. 22(4): 243-298.

Henschel B (2002). Child Labour related Programmes: A Review of Impact Evaluations. *Understanding Childrens Work programme*. World Bank and UNICEF.
http://www.ucw-project.org/pdf/publications/childlabour_impactevaluation.pdf.

Ho, Daniel E., Kosuke Imai, Gary King and Elizabeth Stewart. (2004). Matching as Non-parametric Preprocessing for Reducing Model Dependence in Parametric Causal Inference.

<http://gking.harvard.edu/~les/matchp.pdf>

Huffman, W.E. (1991), Farm and Off-Farm work Decisions: the Role of Human Capital, *The Review of Economics and Statistics*.

Imbens, G. and Angrist, J. (1994), "Identification and Estimation of Local Average Treatment Effects", *Econometrica*, 62(2), 467-75.

Jacoby, H., G. Li and S. Rozelle (2001), Hazards of Expropriation, Tenure Insecurity and Investment in Rural China, *American Economic Review*.

Janvry, A., Fafchamps, M. and E. Sadoulet (1991), Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained, *The Economic Journal*, Vol. 101, No. 409, 1400-1417.

Johnson P N, Misra S K and Ervin R T (1997). A Qualitative Choice Analysis of Factors Influencing post-CRP land use decisions. *Journal of Agricultural and Applied Economics* 29(1), p163-173.

Kalaitzandonakes N G and Monson M (1994). An Analysis of Potential Conservation Effort of CRP Participants in the State of Missouri: A Latent Variable Approach. *Journal of Agricultural and Applied Economics*. 26(1) p200-208.

Key, N., E. Sadoulet and A. de Janvry (2000), Transaction Costs and Agricultural Household Supply Response, *American Journal of Agricultural Economics*, vol82, 245-259.

Kimhi, A. (2004), Family Composition and Off-Farm Participation Decisions in Israeli Farm Households, *American Journal of Agricultural Economics*, 86 (2) (May 2004), pp502-512.

Koenker R (2003). A short course on quantile regression. mimeo CEMMAP/UCL.

Koenker R and Basset G (1978). Regression Quantiles. *Econometrica* 46(1), pp33-50.

Leuven, E., Sianesi, B., 2003. PSMATCH2: Stata module to perform full Mahalanobis and propensity score matching, common support graphing, and covariate imbalance testing". (<http://ideas.repec.org/c/boc/bocode/s432001.html>. Version 1.2.0.)

Li, G., S. Rozelle and J. Hunan, Land Rights, Farmer Investment Incentives and Agricultural Production in China.

Li, G., S. Rozelle and L. Brandt, (1998), Tenure, Land Rights and Farmer Investment Incentives in China, *Agricultural Economics* 19 (1998), pp63-71.

Liu, S., M. Carter and Y. Yao (1998), Dimensions and Diversity of Property Rights in Rural China: Dilemmas on the Road to Further Reform, *World Development* Vol. 26, No. 10, pp. 1789-1806, 1998.

Matsche, I. and T. Young (2004), Off-farm Labour Allocation Decisions in Small-scale Rural Households in Zimbabwe, *Agricultural Economics*, Vol. 30, pp 175-186.

Meyer B D, Viscusi W K and Durbin D L (1995). Worker's compensation and injury duration: Evidence from a natural experiment.

Navarro-Lozano S (2004). Matching, Selection and the Propensity Score: Evidence from Training in Mexico. Mimeo, University of Chicago.

OECD (1996), Fay, R.G. Enhancing the Effectiveness of Active Labor Market Policies: Evidence from Programme Evaluations in OECD Countries, *Labor Market and Social Policy occasional paper No. 18*

Ng S and Pearce D W (2005). The Impact of Forest Policies on Local Communities in China. Mimeo, Department of Law, University College London.

Park A and Wang S (2001). China's Poverty Statistics. *China Economic Review*. 12, pp384-398.

Poterba J M, Venti S F and Wise D A (1995). Do 401(k) contributions crowd out other personal saving?. *Journal of Public Economics*. 58, p1-32.

Project Team for the Forestry Development Strategy for Sustainable development in China (PTFDSSD), 2003. *Forestry Development Strategy for Sustainable Development in China*, China Forestry Publishing House, Beijing.

Quandt, R. (1972), A New Approach to Estimating Switching Regressions, *Journals of the American Statistical Association*, Vol. 67, 306-310.

Reddy S and Minoiu C (2005). Chinese Poverty: Assessing the Impact of Alternative Assumptions. mimeo Columbia University.

Rosenbaum, P. and Rubin, D.B. (1983), "The Central Role of the Propensity Score in Observational Studies for Causal Effects", *Biometrika*, 70, 41-55.

Rosenbaum, P. and Rubin, D.B. (1984), "Reducing Bias in Observational Studies Using Subclassification on the Propensity Score", *Journal of the American Statistical Association*, 79, 516-524.

Sadoulet, E., A. de Janvry and C. Benjamin, (1998), Household Behavior with Imperfect Labor Markets, *Industrial Relations*, Vol. 37, No1, 85-108.

Singh, I., L. Squire and J. Strauss, (1985), *Agricultural Household Models: Extensions, Applications and Policy*, Baltimore: John Hopkins Press for the World Bank, 153-182.

Uchida E, Xu J and Rozelle S (2004). Grain for green: cost-effectiveness and sustainability

of China's conservation set-aside program. *Land Economics* forthcoming.

WWF (2003). Report suggests China's 'Grain-to-Green' plan is fundamental to managing water and soil erosion. <http://www.wwfchina.org/english/loca.php?local=159>.

Xu J and Cao Y (2002). Chapter 4. In Jintao Xu, Eugenia Katsigris and Thomas A. White (2001) (eds). *Implementing the Natural Forest Protection Program and the Sloping Land Conversion Program: Lessons and Policy Implications*. CCICED-WCFGTF. Beijing Forestry Publishing House: Beijing.

Xu J, Eugenia Katsigris and Thomas A. White (2002) (eds). *Implementing the Natural Forest Protection Program and the Sloping Land Conversion Program: Lessons and Policy Implications*. CCICED-WCFGTF. Beijing Forestry Publishing House: Beijing.

Xu, J. (2003), *Social and Economic Evaluation of Steep Land Conversion Program in Shaanxi, Gansu and Sichuan*, commissioned by State Forest Administration.

Xu, J., and Y. Cao. (2002), *The Sustainability of Converting the Land for Forestry and Pasture*, *International Economic Review* (Chinese Academy of Social Sciences), 3-4 2002, pp 56-60.

Xu, Z., Xu, J., Deng, X., Huang, J., Uchida, E. and Rozelle, S. (2004). *Grain for Green and Grain: The impact of China's conservation reserve program on grain prices and food security*. Report submitted to the World Bank.

Yang Y (2001) *Impacts and Effectiveness of Logging Bans in Natural Forests: People's Republic of China*. FAO RAP Publication 2001/08, pp. 81-102.

Zhao Renwei & Li Shi (1997), *Increasing Income Inequality and Its Cause in China*. *Journal of Economic Research*, No.9.

5.11 Appendices

5.11.1 Appendix 1: Procedure for the regression adjusted *DID* estimators (Heckman et al 1998, Navarro-Lozano 2004, Abadie 2005)⁴⁸

In order to undertake Heckman et al's regression procedure we adapt the procedure of Navarro-Lozano (2004) and undertake the following steps in order to estimate the parameter of interest, the average treatment on the treated (*ATT*). The results of each step are discussed in the text.

1. We estimate the propensity score, \hat{P} , using a probit on the dummy for participation and explanatory variables $Z_{it'}$.
2. We keep only the observations of non-participants whose propensity score falls on the support of the treated group.
3. For the regression adjusted estimator we undertake steps a) - d) below. Otherwise we define $Q_{0j} = (Y_{0jt} - Y_{0jt'})$ and $Q_{1k} = (Y_{1kt} - Y_{0kt'})$ and undertake the straight difference in difference estimator or undertake e.g. local linear or local constant (kernel) matching on these values as suggested in points 4-6 below.
 - a) Run a local linear regression of $Y_{0jt'}$ on \hat{P} . Form the residuals $\varepsilon_{0jt'} = Y_{0jt'} - \hat{Y}_{0jt'}$
 - b) Run a local linear regression of each element of $X_{it'}$ on \hat{P} . Let $\hat{X}_{it'}$ be the predicted values. (Note that here one chooses the exclusion restriction since $X_{it'}$, the determinants of the outcome variable, may or may not include all the elements of $Z_{it'}$, the determinants of participation). Form the residuals $\varepsilon_X = X_{it'} - \hat{X}_{it'}$.
 - c) Run a linear regression of $\varepsilon_{0jt'}$ on ε_X and save the estimated parameters of this regression: $\hat{\beta}_{0t'}$.
 - d) Repeat a)-c) for time period t to obtain vector β_{0t} .
 - d) Define $Q_{1k} = (Y_{1kt} - X_t \hat{\beta}_{0t}) - (Y_{0kt'} - X_{t'} \hat{\beta}_{0t'})$ and $Q_{0j} = (Y_{0jt} - X_t \hat{\beta}_{0t}) - (Y_{0jt'} - X_{t'} \hat{\beta}_{0t'})$
4. Run a local linear regression of Q_{0j} on \hat{P} and let \hat{Q}_{0j} be the predicted value.
5. Insert \hat{Q}_{0j} into the equation for ATT_{DID} shown in (5.21) in the text.
6. We then use bootstrapping to obtain standard errors.

⁴⁸ A routine to implement this estimator written for STATA 8.0 and is available from the author upon request.

The attentive reader will notice that the estimation of vectors β_{0t} and $\beta_{0t'}$ is not explicitly defined in Heckman et al (1997) in which only the vector β_{0t} is defined.

The regression/bias adjusted Abadie (2005) estimator requires that the *DID* identification assumption (assumption A-3) holds and that the support of the propensity score for the treated is a subset of that for the untreated. Assumption A-2 is sufficient for this. Given these conditions it can be shown that a linear least squares approximation to the conditional parameter of interest ($ATT(T) = E[Y_1(1) - Y_0(0) | T, D = 1]$) can be given by $T'\beta_0$ where:

$$\beta_0 = \arg \min_{\beta} E \left[P(D = 1|X) \cdot \{\rho_0(Y_1(1) - Y_0(1)) - T'\beta\}^2 \right] \quad (5.30)$$

where as above, $\rho_0 = \frac{D - P(D=1|X)}{P(D=1|X)(1 - P(D=1|X))}$. (See Abadie (2005) for more details). Note that (5.30) implies a weighted OLS regression of T on $\rho_0(Y_1(1) - Y_0(1))$, weighted by $\sqrt{P(D = 1|X)}$. The unconditional (on T) estimate of ATT is then obtained from replacing $Y(1) - Y(0)$ with the predictions from the parametric approximation to the parameter of interest $T'\beta$ equation (5.20) in the text.

5.11.2 Appendix 2: The data

A number of transformations of the data have been undertaken. Of these the most noteworthy have been with regard to crop and livestock prices. Firstly, missing crop prices in the pre-SLCP period were replaced with yearly averages, and where these were not available, the overall average for the pre SLCP periods. This was made possible due to very detailed price data collected from the majority of farmers. In the post-SLCP period, prices were replaced with the overall average. Once prices had been replaced crop incomes were imputed.

With regard to livestock we were occasionally confronted with missing values for revenues or quantities. These were replaced using regression techniques based upon the unit values calculated from those households for which data on revenues and quantities were complete. The unit value for good i is represented by $V(i)$, the quantity by $q(i)$ and the unit value by $p(i)$ and hence the following identity holds: $p(i) = V(i)/q(i)$. We follow Capeau and Dercon (1998) and treat observed revenues and quantities as random variables and use a model which accounts for variations in the quality of livestock in different regions. Hence the identity can be represented as a stochastic model:

$$\ln V_{ik} - \ln q_{ik} = \ln p_{ijk}d_j + \ln \phi_j + \varepsilon_{it}$$

for individual i and good k in location j where the LHS is the stochastic representation of the log unit value and d_j are dummy variables for the towns in which the observation was made. ϕ_i represents an unobserved fixed effect for the town while ε_{it} represents a temporary random innovation. The fixed effect can be thought of as representing the unobserved quality of the livestock sold and is assumed to remain constant over time. The coefficients from a random effects regression using pre and post programme data, which are equal to an estimate of $\ln p_{it}$, are used to replace the livestock prices where they are missing in a particular town using the corrections proposed by Goldberger (1968) for such logarithmic functional forms. See Capeau and Dercon (1998) for details. This represents a common method for valuing subsistence production in rural communities. For all sources of income values were transformed into 2002 prices using the CPI for each region.

Percentiles	
1%	0.10
5%	0.38
10%	0.47
25%	0.63
50%	0.81
75%	0.91
90%	0.95
95%	0.97
99%	0.99
Mean	0.775
Sd	0.175
Observations	274

Table 5.10: The quantiles of the propensity score

5.11.3 Appendix 3. The propensity score

There are a number of conditions with regard to the propensity score that must be satisfied. Firstly, it is useful to summarise this statistic across participants and non-participants. In this way we can see the extent of the common support. In this Appendix we also show the estimates of the propensity score from the second estimation method described in Section 5.6.2.2.

Table 5.10 details the quantiles of the propensity score. Figure 5.5 shows the density of the propensity score for participants and non-participants and reveals the extent to which they share common support: a condition important for the consistency of matching estimators.

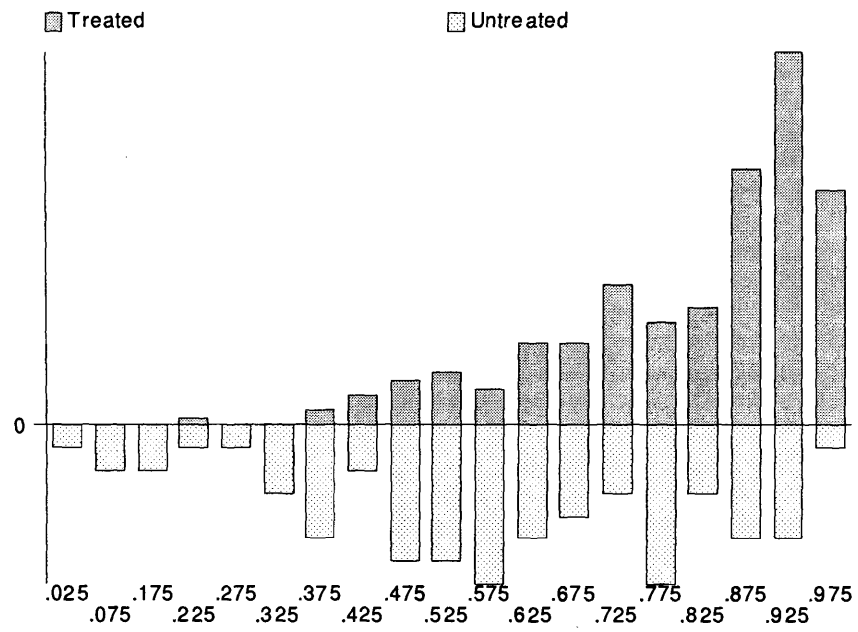


Figure 5.5: The density of the propensity score

5.11.4 Appendix 4. Household level incomes changes and alternative matching techniques

Table 5.11 and 5.12 show the household level treatment effects for different evaluation methods and a comparison of the two matching methods used for the evaluation of per capita incomes.

Income Sources	Household Incomes			
Gross Incomes	Parametric	Stratified	Kernel	Abadie (SP)
Total	-656.52 (682.60)	-48.55 (1038.50)	-204.62 (854.63)	-483.34 (1026.92)
Crop	-1649.43** (268.32)	-1441.27** (272.54)	-1426.09** (258.43)	-1383.67** (267.33)
Crop +SLCP	-10.07 (269.33)	208.76 (248.37)	223.94 (192.80)	126.55 (263.35)
Off-farm	-304.99 (563.59)	580.78 (960.42)	521.51 (854.79)	1297.79 (1645.07)
Livestock	-146.30 (311.75)	-104.92 (227.02)	-167.45 (233.86)	162.50 (249.24)
Forest	-21.76 (38.22)	-49.00 (66.75)	-51.89 (75.08)	-80.38 (81.62)
Net incomes				
Total	-134.63 (682.32)	506.48 (1029.43)	232.77 (864.22)	-90.19 (1073.79)
Crop	1162.11** (244.28)	-1007.16** (220.38)	-1025.48** (246.04)	-1010.59** (255.00)
Crop +SLCP	477.25^ (274.50)	642.87** (287.19)	624.55** (213.89)	499.63* (267.22)
Livestock	112.51 (293.44)	-76.48 (267.92)	-126.05 (210.84)	-95.46 (302.54)
Forest	-101.63 (112.13)	-69.54 (70.28)	-85.09 (62.18)	-121.37 (79.04)

Table 5.11: Household level income changes with different DID estimators

Income Sources	Per capita Incomes	
Gross Incomes	Stratified	Kernel
Total	-14.94 (177.99)	-49.23 (154.89)
Crop	-280.684** (88.99)	-272.91** (79.69)
Crop +SLCP	60.82 (96.19)	68.59 (77.42)
Off-farm	79.70 (160.50)	64.853 188.78
Livestock	-23.241 (37.66)	-33.64 44.30
Forest	-19.27 (17.96)	-19.745 19.33
Net incomes		
Total	53.239 (180.79)	7.77 (187.24)
Crop	-189.85* (89.96)	-196.03** (69.48)
Crop +SLCP	151.646* (74.01)	145.47* (76.34)
Livestock	-25.59 (54.76)	-35.78 (42.90)
Forest	-21.682 (17.25)	-24.68 (16.99)

Table 5.12: Per capita income changes with Stratified and Kernel matching

Outcome Variable	Household		
No off-farm labour	Parametric	Local Linear	Abadie
Off-farm Income	2038.73** (440.75)	2908.76** (531.42)	1000.79** (366.37)
Off farm labour			
Off-farm Income	677.61 (887.90)	1715.26** (374.76)	1161.12* (577.50)

Table 5.13: The ATT for household off-farm labour incomes for participants and non-participants in that market

	Parametric	Local linear diffs	Abadie
Constant	1,009.57 (479.88)*	-169.58** (30.34)	382.55 (284.82)
Hezhang	-161.48 (434.07)	-42.34 (91.76)	294.42 (337.52)
Jingyuan	-123.23 (514.18)	318.92^ (184.74)	417.21 (413.82)
Pengyang	-274.85 (454.05)	-310.21** (99.10)	245.42 (399.95)
Yuanzhou	-93.78 (430.69)	-38.95 (30.55)	405.51 (312.74)
Agprod	-1.30 (0.29)**	1.31* (0.50)	-1.09 (0.35)**
Lab	-0.26 (0.19)	1.19** (0.12)	-0.21 (0.18)
Treat (α)	340.30* (151.67)	-	-
Observations	286	70	286
R-squared	0.09	-	0.12

Table 5.14: Regression adjustment estimates for net income per capita

5.11.5 Appendix 5: Regression adjustment results

Tables 5.14 and 5.15 show the results of the regression adjustment regressions for each of the estimators considered in the text. Abadie (2005) shows that there is a broad similarity between each of these models since they can be thought of in terms of a differenced version of equation (5.20) in Section 5.5.2.2:

$$Y_k(1) - Y_k(0) = \delta + X'_k\pi + \alpha.D_k(1) + (v_k(1) - v_k(0)) \quad (5.31)$$

where $\pi = \pi(1) - \pi(0)$. Cast in this light the parameters of the conditioning variables are time varying and hence the model admits time invariant regressors for regression adjustment. The similarity with the local linear approach of Heckman et al (1997) described above ought to be clear since in that case a matching estimator is generated for each time period based upon the non-participant data and hence separate parameters are estimated in each time period, that is we effectively estimate $\pi(1)$ and $\pi(0)$ separately. These parameters are shown in Table 5.15 whereas 5.14 reflects the differences between them. The Abadie model requires a parametric approximation to the differences in the outcome variable and we choose the same regressors for this, allowing a comparison.

Our choice of regressors reflects a reduced form whereby the impact of the programme is entirely captured by the participation dummy or the residuals in the case of the non-parametric estimators. Therefore we limit ourselves to district level dummies, agricultural productivity and total labour days supplied. These allow heterogeneous impacts as required in our case. Many of the parameters are significant.

	Local linear pre	Local linear post
Constant	50.32 (193.55)	-119.25 (159.00)
Hezhang	-333.20 (595.00)	-375.55 (469.44)
Jingyuan	2.523.28* (1162.90)	2.842.21** (986.87)
Pengyang	-160.67 (595.07)	-470.88 (560.57)
Yuanzhou	91.24 (63.63)	-127.70* (53.21)
Agprod	-1.18 (4.07)	0.13 (0.62)
Lab	2.05* (0.85)	3.24** (0.56)
Observations	69	67
R-squared	0.24	0.47

Table 5.15: Local linear regression adjustment for net incomes per capita

5.11.6 Appendix 6. Poverty alleviation: Alternative estimators

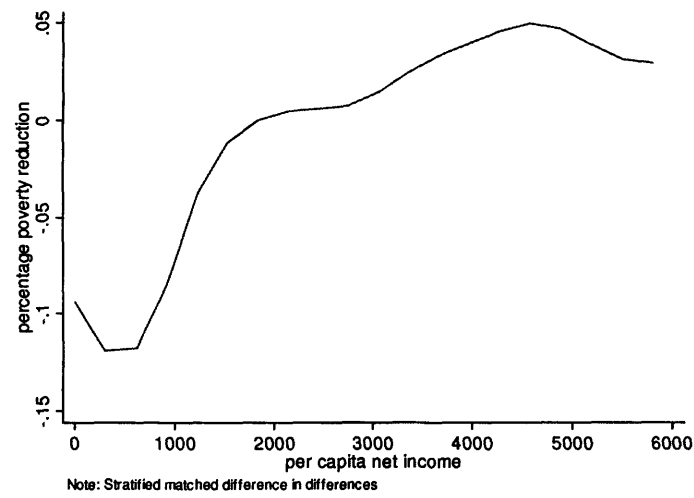


Figure 5.6: SLCP impact on income poverty: Stratified *DID* matching

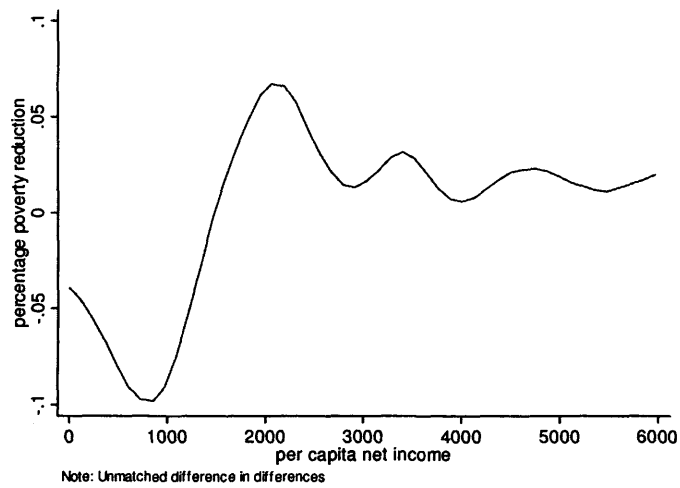


Figure 5.7: SLCP impact on income poverty: Unmatched *DID* estimator